CONTRACT NO. 95-340
FINAL REPORT
APRIL 1999

Three-Way Catalyst Technology for Off-Road Equipment Powered by Gasoline and LPG Engines

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

THREE-WAY CATALYST TECHNOLOGY FOR OFF-ROAD EQUIPMENT POWERED BY GASOLINE AND LPG ENGINES

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APRIL 1999

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ACKNOWLEDGMENTS

This project was performed by the Department of Emissions Research in the Automotive Products and Emissions Research Division at Southwest Research Institute, San Antonio, Texas. Jeff J. White, Manager of the Certification, Audit, and Compliance Section, was the Project Manager. Melvin N. Ingalls, Principal Engineer, served as the Principal Investigator for Phase 1, and James N. Carroll, Senior Research Engineer, served as Principal Investigator for Phase 2. Mr. Lit-Mian Chan of Automotive Emissions Control International, Inc. performed the cost effectiveness analysis.

The assistance of the Technical Advisory Committee, made up of representatives from the off-road engine industry, is gratefully acknowledged. Members of the committee were:

Ford Power Products - Jim Hudzinski
ITA - Gary Cross
NACCO - Bob Downey, Rick Steele
Nissan - George Maes
WIS-CON - Jerome Berti
MECA - Dale McKinnon
ASEC - John Howitt
Zenith - Jim Gorny
IMPCO - Bob Burrahm (now Brad Garner)
Algas - Roger Shugart
EMA - Kate Drakos
GM - Charles Elder

This report was submitted in fulfillment of ARB Contract No. 95-340, "Three-way Catalyst Technology for Off-Road Equipment Powered by Gasoline and LPG Engines," by Southwest Research Institute under the sponsorship of the California Air Resources Board and the South Coast Air Quality Management District. Work was completed as of March 1999.

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ABSTRACT

Research was done to demonstrate the feasibility of using closed-loop three-way catalyst (TWC) technology in off-road large spark-ignited (LSI) engine applications to meet California State Implementation Plan (SIP) emission reduction goals. Available technology was investigated for applicability to engines in this category. A Technical Adviry Committee, made up of engine and equipment manufacturers and representatives from industry organizations, was formed to provide input on technical issues. Appropriate test cycles were recommended, and five representative engines were selected and baseline emission tested. Total feasible emission reductions were calculated. The retail price equivalent (RPE) for the recommended emission control technology was determined, and cost-effectiveness was calculated. Emission standards necessary to meet SIP goals were recommended.

Two emission reduction systems, incorporating three-way catalysts with electronic fuel control, were designed, constructed, and emission tested. Emissions durability testing was then performed to demonstrate the feasibility of application of these technologies to category equipment. Results showed that low emission levels, easily meeting CARB's newly adopted LSI emission standards, could be achieved.

Engine identification is coded in report sections presenting emission results. Manufacturers agreed to loan engines to the program for testing, providing results were coded to maintain manufacturer confidentiality.

EXECUTIVE SUMMARY

Background - In order to meet ambient air standards in California by the year 2010, emissions reductions will be required from off-road equipment using large spark ignited (LSI) engines, as delineated in mobile source control strategies M11 and M12 of the California State Implementation Plan (SIP). The purpose of this research was to demonstrate the technical feasibility of using closed-loop three-way catalyst (TWC) technology in off-road LSI engine applications to meet SIP emission reduction goals. The project included three basic objectives: 1) determine that the transfer of TWC technology to off-road gasoline and LPG engines is feasible, 2) define appropriate emission test procedures for category equipment, and propose emission standards which will enable attainment of SIP goals, and 3) demonstrate that TWC technology can meet the proposed standards by applying the technology to off-road engines and performing emissions durability testing.

Methods - Category equipment types were investigated, and detailed information was compiled about engine models and configurations. A literature search was conducted for applicable technology; not only was TWC technology investigated, but other, previously used automotive emission control technologies were investigated also. Cost effectiveness of these technologies was determined using standard techniques.

Results - A Technical Advisory Committee (TAC), made up of engine and equipment manufacturers and representatives from industry organizations, was formed to provide input on technical issues. TAC members also provided engines for baseline tests and technology demonstrations.

Two test cycles were recommended for category equipment. The ISO 8178 seven-mode C2 cycle was recommended for variable speed applications such as forklifts and airport ground support equipment, and the five-mode D2 cycle was recommended for constant speed applications such as generator sets. Baseline emissions tests were run on five engines using the recommended cycles. Testing was performed with both gasoline and LPG. From the baseline emission results and the individual engine emission reductions required to meet SIP goals, emission standards for THC and NO_x were recommended.

Total emission reductions were calculated based on baseline emission results, equipment population and usage, and technologically feasible emission reductions. The retail price equivalent (RPE) for the recommended emission control technology was determined, and cost-effectiveness was calculated.

A primary objective was to demonstrate that TWC technology could meet the proposed standards by applying the technology to off-road engines and performing emissions durability testing. Systems were designed and installed on Engines B and E. Both systems included closed-loop, stoichiometric fuel control, and three-way catalysts. Baseline controlled emission data was taken, and then the two engines were placed in service for 250 hours.

Engine B was installed in a forklift, and Engine E was coupled to a water pump and placed in service as a pump drive. Both engines successfully completed their service intervals, although Engine B suffered a fuel contamination incident which required cleaning of the fuel control valve, and Engine E required a setting change in its software to enable it to run properly in cooler weather.

During the course of this project, the California Air Resources Board adopted emission standards and test procedures for this category. Both Engines B and E met CARB's LSI standards, as summarized below, except for Engine E's CO emissions following durability, which slightly exceeded the standard.

DEVELOPMENTAL ENGINE EMISSION RESULTS

Test Description	Emissions, g/hp-hr				BSFC, lb/hp-hr
	HC	NO_x	HC+NO_x	CO	
Engine B, C2 Cycle, LPG Fuel					
Original baseline, pre-control	0.94	11.7	12.6	7.37	0.526
Developmental baseline, CL control, TWC - 0 hr. Reduction from original baseline	0.19 80%	0.01 100%	0.20 98%	4.13 44%	0.554 -5%
Durability result, CL control, TWC - 250 hrs. Reduction from original baseline	0.08 91%	0.34 97%	0.42 97%	3.15 57%	0.558 -6%
Engine E, D2 Cycle, Gasoline Fuel					
Original baseline, pre-control	9.86	1.65	11.5	449	1.051
Developmental baseline, CL control, TWC - 0 hr. Reduction from original baseline	0.25 97%	1.42 14%	1.67 85%	28.4 94%	0.881 16%
Durability result, CL control, TWC - 250 hrs. Reduction from original baseline	0.17 98%	0.11 93%	0.28 98%	42.2 91%	0.921 12%
CARB LSI Standards (NMHC+NO_x)			3.0	37	

Conclusions - It was determined that it is feasible and cost effective to transfer advanced emission reduction technologies to off-road gasoline and LPG engines. A limited durability demonstration showed that CARB's new LSI emission standards can be met through application of appropriate emission reduction technology.

One remaining issue in the development of this new regulation is the question of long-term catalyst durability. CARB's Tier 2 LSI regulation requires these standards be met throughout a useful life period of 5000 hours or seven years. Further study is needed to determine whether commercial catalysts can perform acceptably over a period of 5000 hours, and whether equipment fuel system calibrations are sufficiently stable in long term operation. These questions need to be answered to provide confidence in the technologies industry will be relying on to meet this new rule.

I. INTRODUCTION

In November 1994, the Air Resources Board (ARB) adopted a State Implementation Plan (SIP) For Ozone for submission to the U.S. EPA, which included emission control strategies for achieving attainment of federal ambient air quality standards. The mobile source control portion of the SIP contained 16 control measures, designated M1 to M16. Control measures M11 and M12 concern industrial equipment powered by gasoline and LPG engines from 25 to 175 horsepower. Measure M11 is for control of the 60 percent of the industrial equipment that is not preempted by the U.S. EPA. Measure M12 is for industrial equipment that is preempted by the U.S. EPA, including diesel-powered equipment, and engines used in farm and construction equipment. This project is concerned primarily with non-preempted equipment covered by control measure M11.

Currently neither the ARB or the U.S. EPA have emission standards for the equipment covered by measures M11 and M12. However, since many of the engines in this group are similar to, or derived from, early 1980s automobile engines, it was expected that it should be possible to transfer three-way catalyst (TWC) technology to these industrial equipment engines without encountering any major difficulties.

A. Objectives

The purpose of this project was to demonstrate the technical feasibility of utilizing closed-loop TWC technology in off-road gasoline and/or liquefied petroleum gas (gasoline/LPG) engine applications in order to meet emission reduction goals established by the SIP. The project included three basic objectives:

1. Determine that the transfer of TWC technology to off-road gasoline and LPG engines is feasible.

2. Define appropriate emission test procedures for category equipment, and propose emission standards which will enable attainment of SIP goals.

3. Demonstrate that TWC technology can meet the proposed standards by applying the technology to off-road engines and performing emissions durability testing.

B. Approach

Both an analysis phase and a testing phase were required to fulfill the objectives of this project. The analysis phase examined the types of equipment used in the M11 category, and compiled detailed information about engine models and configurations. Equipment population information was reviewed and summarized. A literature search was conducted for applicable technology; not only was TWC technology investigated, but other, previously used automotive emission control technologies were investigated also. Cost effectiveness of these technologies was determined using standard techniques. Emission reductions required for individual engines to meet the M11 category SIP emission reduction goals were calculated.

A Technical Advisory Committee (TAC) was formed with representatives from equipment, engine, fuel system, and catalyst manufacturers, and industry associations. The purpose of the TAC was to provide technical information and support to the project in the following areas:

- Category equipment population and sales
- Emission reduction technology development and manufacturing issues
- Typical operating modes for off-road equipment
- Recommendations regarding test cycles and procedures
- Emission reduction technology costs
- Procurement of five program engines
- Engines and fuel types for system demonstrations
- Support for system development and durability testing.

With input from the TAC, appropriate test cycles and procedures for category equipment were selected. These procedures were then used to obtain baseline emissions data on the five program engines. The average emissions from these tests, together with emission test results from other studies that used the same test cycles, were used to define average baseline emission factors. Baseline emission factors, together with the emission reductions calculated to be necessary to meet SIP goals, were used to determine the recommended emission standards for the M11 category.

II. PHASE I - TECHNOLOGY FEASIBILITY ASSESSMENT

A. Task 1.1 - Technology Review

1. Equipment Inventory and Engine Model Information

a. Equipment in Category

Equipment investigated in this project is based on California SIP control measures M11 and M12, and is defined as "Industrial Equipment, Gasoline and LPG." Table 1 lists the equipment included in this category as taken from the project RFP, with subsequent revisions made by ARB staff.

TABLE 1. LIST OF INDUSTRIAL EQUIPMENT (SIP CATEGORY M11)

Industrial equipment is defined as that equipped with engines 25 horsepower or greater that is not construction or farm equipment. All equipment types with engines 25 horsepower or greater are presumed to be construction or farm equipment, with the exception of the equipment types listed below, which have been determined not to be construction or farm equipment.

- Airport Ground Support Equipment (GSE)
- Forklifts (not rough terrain) less than 50 horsepower, not powered by diesel engines
- Generator Sets
- Mining Equipment (surface) not otherwise primarily used in the construction industry
- Other Industrial Equipment
- Other Materials Handling
- Refrigeration Units less than 50 horsepower
- Scrubbers/Sweepers
- Speciality Vehicles
- Turf Care Equipment.

Since the subject equipment category is what remains when most other off-highway equipment is removed, and since it contains some broadly phrased items such as "Other Industrial Equipment," it is important to know what is <u>not</u> included in this category. This category specifically excludes construction and farm equipment, the control of which is preempted by the U.S. EPA. Table 2 lists equipment types that are considered construction and farm equipment.

TABLE 2. LIST OF CONSTRUCTION AND FARM EQUIPMENT

The following equipment types have been determined to be construction or farm equipment:

Aerial devices: vehicle mounted
Asphalt recycler/reclaimer, sealer
Augers: earth
Back-hoe
Backpack compressors
Baler
Boring machines: portable line
Breakers: pavement and/or rock
Brushcutters/clearing saws 40 cc and above (blade capable only)
Burners: bituminous equipment
Cable layers
Chainsaws 45 cc and above
Chippers
Cleaners: high pressure, steam, sewer, barn
Compactor: roller/plate
Compressors
Concrete buggy, corer, screed, mixer, finishing equipment
Continuous digger
Conveyors: portable
Crawler excavators
Crushers: stone
Cultivators: powered
Cutting machine
Debarker
Detassler
Drills
Dumper: small on-site
Dusters
Elevating work platforms
Farm loaders: front end
Feed conveyors
Fertilizer spreader
Forage box/haulage and loading machine
Forklifts: diesel and/or rough terrain
Harvesters, crop
Jackhammer
Light towers
Mixers: mortar, plaster, grout
Mowing equipment: agricultural
Mud jack
Pavers: asphalt, curb and gutter
Pipe layer
Plows: vibratory
Post hole diggers
Power pack: hydraulic
Pruner: orchard
Pumps 40 cc and above
Rollers: trench
Saw mill: portable
Saws: concrete, masonry, cutoff
Screeners
Shredder/grinder
Signal boards: highway
Silo unloaders
Skidders
Skid-steer loaders
Specialized fruit/nut harvester
Sprayers: bituminous, concrete curing, crop, field
Stump cutters, grinders
Stumpbeater
Surfacing equipment
Swathers
Tampers and rammers
Tractor: compact utility
Trenchers
Troweling machines: concrete
Vibrators: concrete, finisher, roller
Welders
Well driller: portable
Wheel loaders

b. Equipment Inventory

The ARB informed us that a 1992 report by Booz Allen & Hamilton entitled: "Off-Road Mobile Equipment Emission Inventory Estimate," [1] was the basis for the ARB SIP inventory of Industrial Equipment. At the direction of ARB staff, however, a more recent inventory included in "Documentation of Input Factors for the New Off-Road Mobile Source Emissions Inventory Model,"[2] complied by EEA, was to be used as the inventory for this project. The classes of equipment used in the EEA study did not exactly match the equipment specified in the RFP for this project. Nevertheless, the equipment categories set forth at the beginning of this project (Table 1) were matched as closely as possible with the EEA categories so that the population could be obtained from the ARB off-road emission inventory model.

Table 3 lists the estimated statewide population of each of the M11 categories in the model. From the EEA inventory, the number of engines in the M11 category in the state is not large, totaling only 22,139 in 1990 and 26,671 in 2010. While the gaseous fuel units are listed as CNG, the numbers are too large for CNG engines alone, and for this study are considered to include both LPG and CNG fueled engines.

TABLE 3. INVENTORY OF M11 EQUIPMENT IN CALIFORNIA

ASC	Category	Fuel[a]	HP Class[b]	1990 Pop.	2010 Pop.
2266003010	Aerial Lifts	C4	50	615	786
2266003010	Aerial Lifts	C4	120	363	464
2266003020	Forklifts	C4	50	2776	3543
2266008025	Air Conditioner	C4	175	4	7
2266008035	Baggage Tug	C4	120	77	126
2266008040	Belt Loader	C4	120	16	27
2266008050	Cargo Loader	C4	120	4	7
2266008065	Forklift	C4	50	176	289
2266008090	Lift	C4	120	5	8
2266008100	Other	C4	50	15	25
2265003010	Aerial Lifts	G4	50	615	688
2265003010	Aerial Lifts	G4	120	363	407
2265003020	Forklifts	G4	50	1189	1330
2265003030	Sweepers/Scrubbers	G4	50	1122	1255
2265003030	Sweepers/Scrubbers	G4	120	868	971
2265003030	Sweepers/Scrubbers	G4	175	115	129
2265003040	Other General Industrial Equipment	G4	50	307	344
2265003040	Other General Industrial Equipment	G4	120	199	223
2265003040	Other General Industrial Equipment	G4	175	12	14
2265003050	Other Material Handling Equipment	G4	50	63	71
2265003050	Other Material Handling Equipment	G4	120	187	210
2265006005	Generator Sets	G4	50	4854	5614
2265006005	Generator Sets	G4	120	5206	6020
2265006005	Generator Sets	G4	175	1634	1890
2265008015	A/C Tug, Narrow Body	G4	175	37	61
2265008025	Air Conditioner	G4	175	0	0
2265008030	Air Start Unit	G4	175	0	0
2265008035	Baggage Tug	G4	120	557	912
2265008040	Belt Loader	G4	120	262	430
2265008050	Cargo Loader	G4	120	79	131
2265008060	Deicer	G4	120	25	40
2265008065	Forklift	G4	50	75	124
2265008075	Ground Power Unit	G4	175	61	101
2265008090	Lift	G4	120	121	198
2265008100	Other	G4	50	137	226

[a] Fuel type: C4 = LPG or CNG (4-stroke), G4 = gasoline (4-stroke) [b] HP Class = Upper boundary of HP range

From an examination of Table 3, it appears that generator sets (between 25 and 50 horsepower) are the most populous equipment type in this category, with forklifts (between 25 and 50 horsepower) being the second most populous. Therefore, these two equipment types received the most emphasis in Phase 1 of this project.

c. Engine Manufacturers, Models, And Configurations

The various engine models and configurations used in equipment in the M11 category were investigated. The June 1996 issue of "Diesel Progress - Engines and Drives,"[3] listed manufacturers of off-road engines covering all horsepower ranges of diesel-, gasoline-, and gaseous- (LPG, CNG, and LNG) fueled engines. Another list of off-road engines in the 25 to 175 horsepower range was taken from the gasoline engine summary in the 1997 Diesel and Gas Turbine Worldwide Catalog.[4] A third source of engine model information was a forklift database by K-III Directory Corp.[5] Information from all three sources was combined in Table 4.

A total of 17 engine manufacturers with gasoline engines rated between 25 and 175 hp are listed in Table 4. Not all of the manufacturers that are listed have engines in equipment sold in the U.S. Nevertheless, it is clear that most of the engines available in this equipment category (but not necessarily the most engines in-use) are automotive derivatives.

Since generator sets and forklifts are the two most populous equipment types, an attempt was made to identify the engine manufacturers in the M11 category for these two equipment types. A list of engines, by manufacturer, used in forklifts with engines between 25 and 50 horsepower was assembled from the K-III database, and is given in Table 5. It should be noted that while the fuel is listed as gasoline for all engines, there are a large number of LPG forklifts. All LPG-fueled engines, however, are simply LPG conversions of gasoline engines.

Note that for gasoline forklifts between 25 and 50 horsepower, only five engine manufacturers have been identified. There are undoubtedly some that were missed, but the engines listed in Table 5 are believed to cover the majority of the market. Of these five engine manufacturers, four are automotive engine manufacturers, and the models used in the forklifts are automotive derivatives. Hercules is the only manufacturer of engines that are not automotive derivatives.

An attempt was made to obtain a database of specifications for portable generator sets. Such a database was not available from the K-III Directory Corporation, nor could another source be found. Therefore, a list of gasoline and LPG engines used in generator sets was assembled from information contained in the available engine information.[3,4,6] While almost any of the engines listed in Table 4 could be used with a generator, those that are specifically advertised as available for use as primemovers for generators sets are listed in Table 6. It should be noted that even through there are a large number of gasoline generator sets listed in the inventory presented in Table 3, and those manufacturers in Table 6 expressly advertise their engines for generator applications, we were unable to find gasoline engine powered generator sets at the retail level.

TABLE 4. 1997 BASIC SPECIFICATIONS-GASOLINE ENGINES

Manufacturer	Engine Model	Rated Power Output & Speed (hp)	Rated Power Output & Speed (r/min)	Displacement (L/cyl)	Number of Cylinders & Configurations L: In-Line V: Vee-Type H: Horizontal O: Opposed	Crankshaft Orientation V: Vertical H: Horizontal	Cooling AC: Air-cooled LC: Liquid-cooled
ARROW	VRG	46-80	2400	0.6 TO 0.9	4L&6L	H	LC
BMW MOTOREN GMBH (Ratings to DIN 70020 Standards)		47-295	5200-8500	0.247 - 0.498	20;3,4,6L;8, 12V	H	LC
BRIGGS & STRATTON DIAHATSU LLC		31			3L	H	LC
CHRYSLER, INC.		96	4400	0.5	4L	H	LC
FORD POWER PRODUCTS OPERATIONS (Ratings to SAE J1349 Standards)	VSG 411	44	4000	0.28	4L	H	LC
	VSG 413	50	4000	0.32	4L	H	LC
	LSG 423	119	5400	0.56	4L	H	LC
	CSG 649	213	4200	0.82	6L	H	LC
	CSG 850	185	3800	0.62	8V	H	LC
	WSG 858	236	4200	0.73	8V	H	LC
	LSG 875	339	4600	0.95	8V	H	LC
GM POWERTRAIN (Ratings to ISO Standards)	2.2 L (LPG)	75	3400	0.547	4L	H	LC
	2.2 L (TBI)	95	4400	0.547	4L	H	LC
	2.2 L (MPFI)	110	5200	0.547	4L	H	LC
	3.0 L	145	4800	0.740	4L	H	LC
	3.0 L (TBI)	148	4800	0.740	4L	H	LC
	4.3 L (2-BBL)	184	4400	0.716	6V	H	LC
	4.3 L (4-BBL)	211	4600	0.716	6V	H	LC
	4.3 L (TBI)	211	4600	0.716	6V	H	LC
	5.0 L (2-BBL)	200	4600	0.626	8V	H	LC
	5.0 L (4-BBL)	220	4600	0.626	8V	H	LC
HERCULES ENGINE CO. (Ratings to SAE J1349 Standards)	G1600	61	2800	0.669	4L	H	LC
	G2300	80	2800	0.925	4L	H	LC
	G3400	125	2800	0.925	6L	H	LC
MAZDA	D5	30		0.37	4L	H	LC
	FE	42		0.50			
	F2	46		0.55			
MITSUBISHI MOTORS CORPORATION	Industrial						
	3G8	19	3000	0.219	3L		
	4G1	49	3000	0.367	4L		
	4G6	54-62	3000	0.449 - 0.588	4L		
	6G7	81	3000	0.495	6V		
NISSAN	CG13	42	3600	0.32	L4	H	LC
	H15	43	3400	0.37	L4	H	LC
	H20	54	3200	0.50	L4	H	LC
	H25	62	3200	0.62	L4	H	LC
	TB42	151	3600	0.70	L6	H	LC

TABLE 4 (CONT'D). 1997 BASIC SPECIFICATIONS-GASOLINE ENGINES

Manufacturer	Engine Model	Rated Power Output & Speed (hp)	Rated Power Output & Speed (r/min)	Displacement (L/cyl)	Number of Cylinders & Configurations L: In-Line V: Vee-Type H: Horizontal O: Opposed	Crankshaft Orientation V: Vertical H: Horizontal	Cooling AC: Air-cooled LC: Liquid-cooled
PEUGEOT CITRÖEN ENGINES (Ratings to DIN 6271 and ISO 1585 Standards)	TU9	31	3600	0.239	4L	H	LC
	TU9M	50	6000	0.239	4L	H	LC
	TU1	39	3600	0.281	4L	H	LC
	TU1M	59	6200	0.281	4L	H	LC
	TU3TR	49	3600	0.340	4L	H	LC
	TU3FM	74	5800	0.340	4L	H	LC
	TU3FJ2	96	6800	0.340	4L	H	LC
	TU5JP	87	5600	0.397	4L	H	LC
	XU52CTR	57	3600	0.395	4L	H	LC
	XU52C	91	6250	0.395	4L	H	LC
	XU7JP	99	6000	0.440	4L	H	LC
	XU92CTR	66	3600	0.476	4L	H	LC
	XU92C	107	6000	0.476	4L	H	LC
	XU102CTR	74	3600	0.499	4L	H	LC
	XU10J2C	113	5800	0.499	4L	H	LC
	XU10J2TE	139	4400 - 6200	0.499	4L	H	LC
	XU10J4ACAV	150	6500	0.499	4L	H	LC
	XU10J4TE	192	5000	0.499	4L	H	LC
	ZPJ	150	5600	0.496	6V	H	LC
	ZPJ4	197	6000	0.496	6V	H	CL
RENAULT MOTEURS (Ratings to ISO Standards)	Industrial	35-154	4000-5400	0.227-0.541	4L, 6V	H	LC
TOYOTA (Ratings to SAE J1349 Standards)		34-58	2600-3000	0.37-0.56	4L	H	LC
VOLKSWAGEN AG (Ratings to DIN 70020 Standards and 80/491/EWG)	ADF	67	4000	0.445	4L	H	LC
	ADH	74	5000	0.445	4L	H	LC
VOLVO PENTA (Ratings to ISO 8665 Standards)	230/SP	118	5000	0.575	4L	H	LC
	250/SP	143	5500	0.625	4L	H	LC
	251DOHC/SP	165	5700	0.417	6V	H	LC
	430/DP or SP	173	4500	0.717	6V	H	LC
	431/DP or SP	202	4800	0.717	6V	H	LC
Ratings to SAE J607 Standards)	AQ 131/275	118	5000	0.575	4L	H	LC
	AQ 151/290	143	5500	0.625	4L	H	LC
	AQ 171/290	165	5700	0.625	4L	H	LC
WIS-CON TOTAL POWER WISCONSIN CAST IRON (Ratings to J607A Standards)	W2-1250	26	3600	0.615	2V	H	AC
	VH4D	30	2800	0.441	4V	H	AC
	W4-1770	35	3000	0.441	4V	H	AC
	VG4D	37	2400	0.631	4V	H	AC
	V465D	66	3000	0.725	4V	H	AC
CONTINENTAL	TM20	54	3000	0.671	3L	H	LC
	TM27	71	3000	0.671	4L	H	LC
CONTINENTAL R	R11	35	3600	0.277	4L	H	LC
	R14	47	3600	0.349	4L	H	LC

TABLE 5. ENGINES IN THE 25 TO 50 HORSEPOWER RANGE USED IN FORKLIFTS

Manufacturer	Model	Fuel	Cylinders	Displacement, $in.^3$	Power, hp
Hercules	2.7L	Gasoline	4	163	48
Mazda	F2	Gasoline	4	133	46
Mazda	FE	Gasoline	4	122	42
Mazda	D5	Gasoline	4	91	30
Mitsubishi	4G64	Gasoline	4	143	48
Mitsubishi	4G63	Gasoline	4	122	46
Nissan	H20	Gasoline	4	121	46
Nissan	A15	Gasoline	4	91	36
Nissan	A16	Gasoline	4	91	36
Toyota	4Y	Gasoline	4	136	43

TABLE 6. ENGINE MODELS THAT MANUFACTURERS ADVERTISE AS AVAILABLE FOR GENERATOR SETS

Manufacturer	Model	Cylinders	Displacement, liters	Continuous power (hp)
Ford Power Products	LRG 423 CSG 649 LSG 875	I4 I6 V8	2.3 4.9 7.5	32 68 117
GM Powertrain	Various	I4 to V8	Various	Various
Hercules Engine Co.	G1600 G2300 G3400	I4 I4 I6	2.7 3.7 5.6	40 58 87
Volkswagen	Various	I4	Various	Various
WIS-CON	TM20 TM27 VG4D V465	3 4 4 4	2.0 2.7 2.5 2.9	38 50 32 48

2. Evaluation of Emission Control Technology

It was requested that two emission control strategies be investigated: one using the best available technology, and one based on older technology with a lower cost. The best available technology was the most readily defined and was investigated first.

a. Best Available Technology

Since most engines used in generator sets and forklifts are automotive derivatives, emission control technologies for these engines can focus on current automotive technologies, with consideration for the special problems of generators and forklifts (compact design, exhaust temperatures, etc.). The best available automotive technology utilizes three-way catalyst with closed-loop electronic fuel injection. A number of examples of the application of these technologies to category equipment have been reported in the literature over the past several years, but many of these reports do not include any discussion of emission reductions achieved. Three examples that do include emission reduction data are discussed below.

The first example is from an SwRI study conducted for ARB in 1992.[7] As part of that project, SwRI tested a 2.7 liter, gasoline fueled, 60 horsepower utility engine, using the ISO 8178-G1 test cycle. In stock condition, the engine had a non-feedback carburetor that was calibrated relatively rich (~13.1 A/F). The engine was fitted with a closed loop control system and a three-way catalyst, then tested again using the same test cycle. The closed loop three-way system reduced the emissions below baseline by 96 percent, 98 percent, and 94 percent for THC, CO, and NO_x, respectively.

The second of these examples is from work done by SwRI for the Railroad Commission of Texas.[8] In this study, a Nissan H20 engine was tested in several configurations using both LPG and CNG fuel. Using the ISO 8178-C2 cycle and LPG fuel, a closed loop, three-way catalyst system reduced the emissions below baseline by 76 percent, 94 percent, and 50 percent for NMHC, CO, and NO_x, respectively.

The third example is from information received from Engine Control Systems, Ltd. (ECS) which is a Canadian company that produces an aftermarket closed loop, three-way catalyst system marketed under the trademark "Terminox." In their correspondence[9], they presented results from tests of their system installed on a Toyota 5R, 2.0 liter, 45 hp engine that had been converted to LPG. The tests were performed by Environment Canada using several variants of the ISO eight-mode procedure. Using an optimized ECM program, ECS reported emission reductions of 98.7 percent, 99.3 percent, and 87.4 percent for HC, CO, and NO_x, respectively. ECS says it currently has systems installed on Clark and NACCO equipment.[9]

Emission results from these three sources are summarized in Table 7. The average reduction from baseline for these systems is 90 percent for HC and 77 percent for NO_x. These results are considered sufficient to demonstrate that it is feasible to install automotive-type, three-way catalyst, closed loop, electronic fuel injection systems on engines in the M11 category; and that the individual engine emissions reductions can probably meet the SIP reductions required for NO_x, but may require further development to meet the reductions required for HC.

TABLE 7. EMISSION REDUCTIONS FROM CLOSED-LOOP, THREE-WAY CATALYST SYSTEMS ON OFF-ROAD ENGINES

Reference	Engine	Test Procedure	Fuel	Emissions Reductions, %		
				HC	CO	NO_x
7	"60 HP"	ISO 8178-G1	Gasoline	96	98	94
8	Nissan H20	ISO 8178-C2	LPG	76	94	50
9	Toyota R5	ISO 8178-C1	LPG	98	99	87
			Average	90	97	77

b. Lower Cost Technology

At the start of this project, it was hypothesized that it might be possible to obtain the required SIP emission reductions using older technology that might result in a less costly system. Automotive emission standards in the mid-to-late 1970s required about a 70 percent reduction in HC and a 50 percent reduction in NO_x, compared to uncontrolled cars of the late 1960s. Thus, technology of this era might be applicable to M11 category engines. Based on SwRI experience in developing and testing such technology, the following emission control methods were investigated:

- Air-fuel ratio calibration
- Spark timing calibration
- EGR
- Air injection
- Improved open loop carburetor
- Oxidation or three-way catalyst.

Each of these items is discussed individually, roughly in order of increasing cost, in the paragraphs below. An estimate of the emission reduction obtainable with each method will be presented. Estimated emissions reductions from selected combinations of these methods will also be discussed.

(1) Air-Fuel Ratio Calibration

Engine exhaust emissions vary with air-to-fuel (A/F) ratio as shown in Figures 1, 2, and 3, all taken from Reference 10. It has been found in laboratory tests at SwRI, that most industrial engines are calibrated richer than stoichiometric. As can be seen from Figures 1 to 3, if the engine A/F ratio is shifted from rich toward stoichiometric, HC and CO will be reduced, but NO_x will be increased. As an added benefit, fuel consumption will also be decreased. The amount of HC and CO reduction and NO_x increase resulting from this shift depends on the initial A/F calibration of the individual engine.

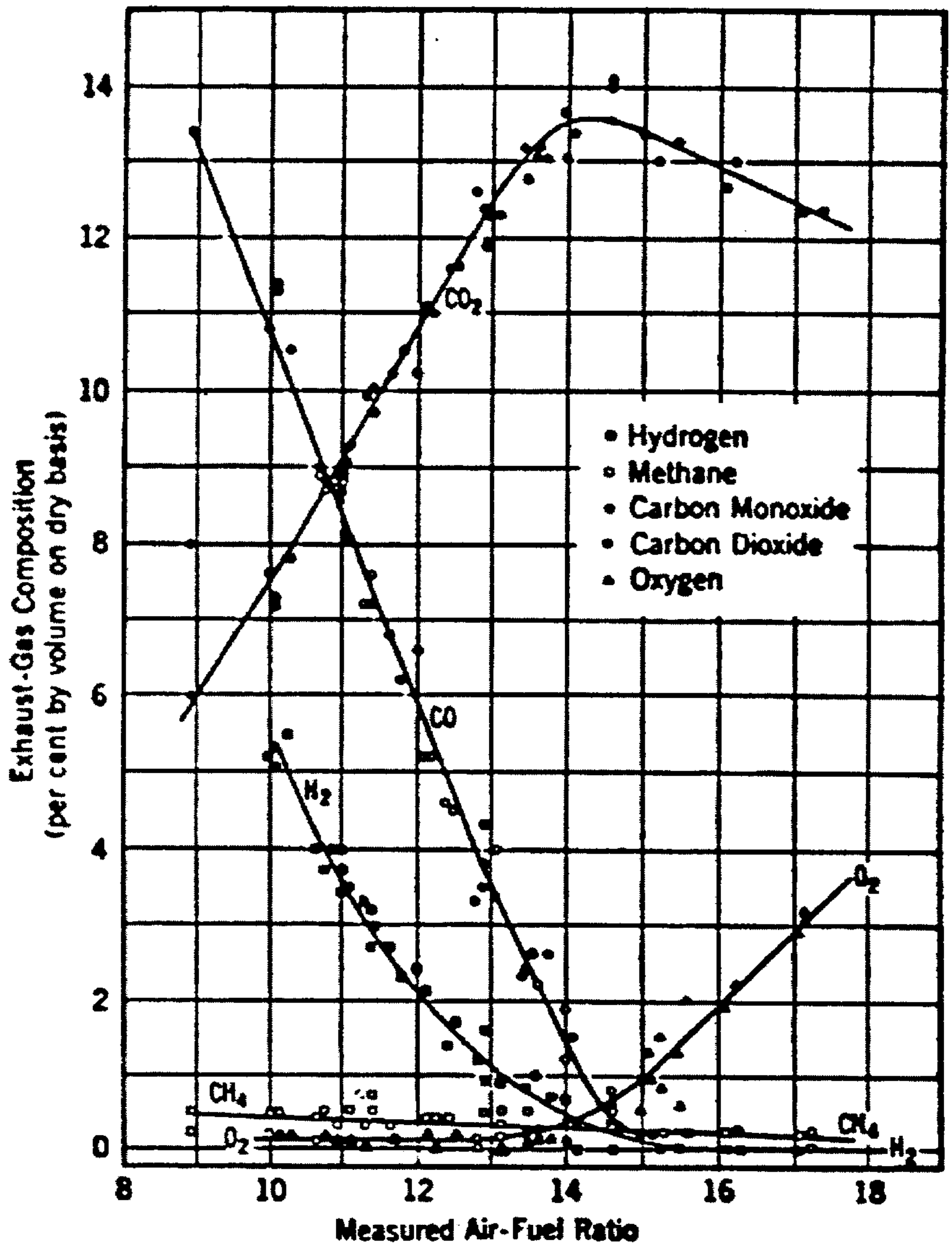

FIGURE 1. EXHAUST GAS CONCENTRATION VERSUS MEASURED AIR-FUEL RATIO

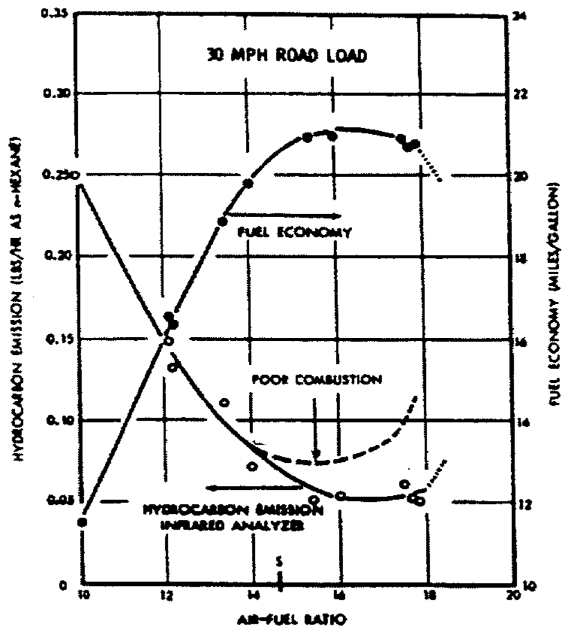

FIGURE 2. EFFECT OF AIR-FUEL RATIO ON EXHAUST HYDROCARBONS AND FUEL ECONOMY AT MODERATE ENGINE LOAD

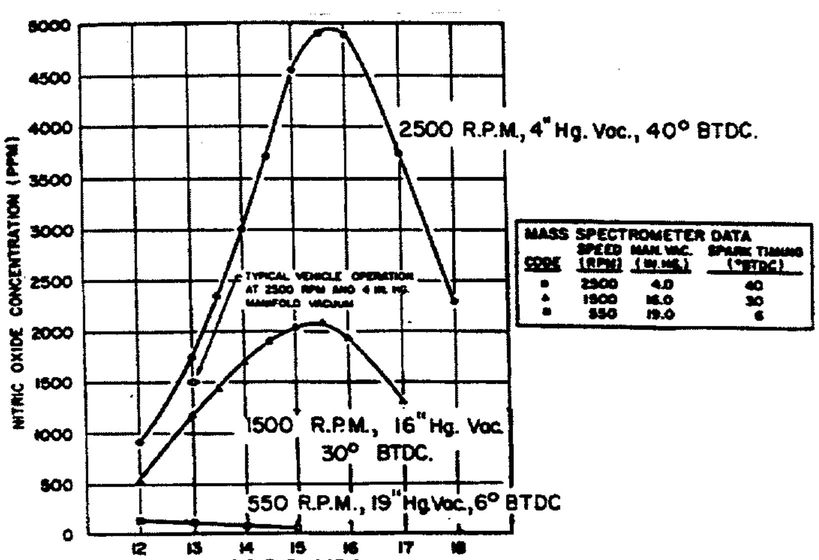

FIGURE 3. EFFECT OF AIR-FUEL RATIO ON NITRIC OXIDE (NO) CONCENTRATION AT THREE DIFFERENT ENGINE CONDITIONS

From experience, typical A/F ratios for industrial engines are approximately 13:1. From Figure 2, it can be seen that, at a moderate load, shifting the carburetor calibration from 13:1 to 14:1 could reduce HC approximately 30 percent, while reducing fuel consumption approximately 10 percent. Figure 3 indicates that going from 13:1 to 14:1 could almost double the NO_x concentration at 2000 rpm and WOT.

As would be expected, emission levels are affected by engine speed and load. Therefore, the selection of test cycle is important when estimating emission changes. A recent study at SwRI on an LPG fueled industrial engine[8] demonstrated the change in HC from shifting the A/F from rich to stoichiometric with an open loop carburetor using the ISO 8178-C2 cycle. Table 8, taken from Reference 8, shows two tests using the same hardware. Test A is at stoichiometric, and Test B is richer by approximately 0.6 A/F. The 0.6 A/F change from rich to stoichiometric results in a 4 percent decrease in NMHC, a 63 percent decrease in CO, and 13 percent increase in NO_x. Thus, while theoretical considerations indicate that enleanment can reduce HC considerably at a single engine condition, for actual test cycles, the HC reduction is smaller.

TABLE 8. CHANGE IN EMISSIONS WITH AIR-FUEL RATIO FOR 2.0 LITER, 4 CYLINDER INDUSTRIAL ENGINE

		Brake Specific Emissions, g/hp-hr			
Test No.	Fuel	NMHC	CO	NOx	λ
B	LPG	2.3	27	15	≈0.96
A	LPG	2.2	10	17	≈1.00

λ = (actual A/F ratio) / (stoichiometric A/F ratio)
λ <1 is fuel rich, >1 is fuel lean

It should also be noted that industrial engines are generally calibrated rich for more dependable operation, and to make up for deficiencies in carburetion. Thus, HC emission reductions from changing A/F ratio are not obtainable without a good quality carburetor. The carburetor used must repeatably maintain A/F ratio over the range of engine operation required by the application. If such a carburetor were not already installed on the engine, HC reduction by A/F ratio change would not be a no-cost item. Enleanment may also cause problems in engine operation that would have to be addressed by changes in engine design. Without such changes in carburetion and engine design, the end user could simply adjust the carburetor richer (assuming such adjustment is possible) to obtain what is considered more satisfactory in-use operation, and the emission improvement could be lost.

(2) Spark Timing Calibration

As ignition timing is retarded, HC and NO_x generally decrease. These reductions, however, are accompanied by an increase in fuel consumption.[10] Ignition retard was used extensively for HC control at engine speeds up to about 1200 rpm, in automobiles during the late sixties.[11,12] Ignition timing retard at other engine conditions was used during the early seventies for NO_x control. This spark retard caused increased heat rejection into the cooling water, particularly at idle.[11] Thus, cooling capacity and idle speed both had to be increased.

Theoretically, HC reductions of greater than 50 percent are possible with spark timing retarded to the area between 0 and 10 degrees BTDC, but with as much as a 20 percent increase in fuel consumption.[10] An SAE paper by GM in the late sixties showed approximately a 30 percent reduction in HC at idle with about 12 degrees ignition retard.[11]

At high loads, and A/F ratios near stoichiometric, a 20 degree spark timing retard can decrease NO_x concentration in the exhaust by as much as 40 percent.[10] Again, an appreciable fuel consumption increase results from the spark retard. A GM study in the mid-seventies[13] showed a 17 percent reduction in brake specific NO_x (g/hp-hr), at a moderate engine speed and load, with a 20° spark retard from MBT (minimum advance for best torque). If spark retard were used on engines with conventional distributors, it is possible that the HC and NO_x reductions would not actually occur in the field, since the end user could simply advance the spark timing to obtain lower fuel consumption.

The point of this discussion is that by judicious choice of A/F ratio setting and spark retard, it is possible to reduce HC and NO_x. However, if large emissions reductions are sought by retarded timing, fuel consumption will increase noticeably. In addition, some engine and engine system design changes may be required.

(3) EGR

EGR is a basic concept for NO_x control of spark ignition engines. Standard textbooks on gasoline engine emission control define the amount of NO_x control possible using EGR. Such a presentation is given in Figure 4, taken from Reference 10. Note that Figure 4 is expressed in fuel-air equivalence ratio, rather than air-fuel as is mostly used in this report. Therefore, values less than one are fuel lean, and values greater than one are fuel rich. Experience has shown that 15 percent is about the practical upper limit for EGR. Figure 4 shows that with 15 percent EGR at stoichiometric air-fuel ratio, a maximum NO_x reduction of approximately 50 percent could be expected. Again, engine speed and load affect NO_x production and EGR efficiency, so reductions may vary depending on the test cycle used.

An SwRI internal research project in 1991 investigated applying EGR and air injection to an 8 horsepower gasoline-fueled utility engine. The results from this project were reported in SAE Paper 911805.[14] Emissions were measured using the SAE J1088 six mode procedure. Mode 3 of this cycle (85 percent rated speed, full load) was used to set the EGR rate by observing the power reduction rather than measuring EGR flow. Baseline tests were conducted with the engine running at a rather lean air-fuel ratio of 15.9. The fuel consumption rate decreased about 1.5 percent with EGR addition, and the carburetor did not maintain a constant air-fuel ratio. During Mode 3, with a 10 percent power reduction, a NO_x reduction of about 58 percent was achieved. The weighted emission results for the six mode test showed approximately a 50 percent reduction in NO_x. Exhaust port air injection was also incorporated for the complete modal test, but it was judged not to have had a significant effect on NO_x.

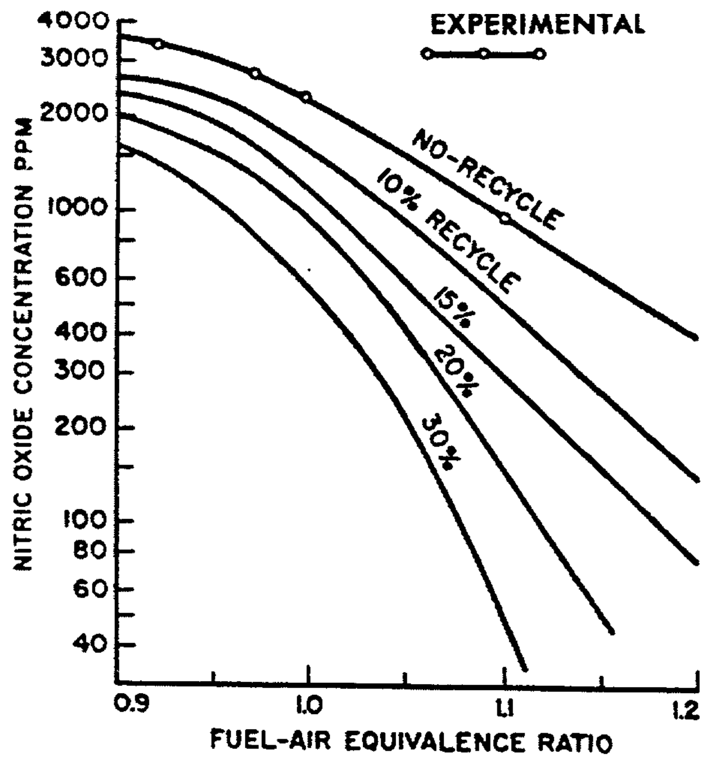

FIGURE 4. NITRIC OXIDE (NO) CONCENTRATION VERSUS FUEL-AIR EQUIVALENCE RATIO WITH VARIOUS EGR (RECYCLE) RATES

From the information collected, it is doubtful that EGR alone can be used to achieve the NO_x reduction required for individual engines by M11, while still maintaining acceptable engine performance. A reduction of approximately 50 percent may be possible, however.

(4) Air Injection

Air injection may be used to reduce HC and CO by thermal oxidation. For CO, the exhaust temperature must be at least 650°C before oxidation will occur. For maximum effectiveness, the air is injected directly into the exhaust valve port. Large reductions in HC and CO are possible using air injection if sufficient temperature is available.

The SwRI study mentioned earlier[14] used air injection for HC and CO control. Composite HC emissions for the six mode test showed a 94 percent reduction on an 8 horsepower engine. The small engine tested ran extremely rich, however, and it is not likely that engines in the M11 category would show such a large reduction.

A 1966 GM study showed approximately a 44 percent reduction in hydrocarbons on the old (obsolete) California 7-mode chassis dynamometer cycle using air injection.[11] In a study done for EPA in the late seventies, SwRI installed an air injection system on a stock heavy-duty 350 CID (5.7 liter) engine.[15] Using the old (obsolete) EPA nine-mode engine dynamometer cycle, HC was reduced 51 percent with air injection into the exhaust port. It should be noted that this study made use of exhaust port liners to keep the exhaust gases as hot as possible.

Two methods of air injection have been used in automotive applications: (1) an air pump, and (2) a pulse air system. The air pump system relies on a belt-driven or electrical pump to continuously supply air. A diverter valve is installed in the air supply line to the exhaust, to dump the air during engine operating conditions where it could cause engine backfire. The air pump can be sized to provide the optimum amount of oxygen needed, so system performance is mostly a function of exhaust gas temperature. Since it requires a pump and some control, this system could be relatively expensive.

The second method, a pulse air system, makes use of the fact that the pressure in the exhaust pipe is cyclic, as the exhaust valves open and close. At some times in the combustion cycle, the exhaust pressure is below atmospheric pressure and air can be sucked into the exhaust pipe using only a reed valve.[16] Pulse air systems were used on automobiles in the U.S. in the mid-1970s, and as recently as 1992, on the Ford Mondeo in Europe. SwRI currently has an industrial engine in the Department of Emissions Research laboratory that is equipped with a pulse air system. While not able to supply as much air as a pump under all engine operating conditions, a well designed pulse air system can provide an adequate amount of air at many operating conditions. Table 9, from reference 16, shows some airflow test data using a GM Pulsair system installed on a 350 CID engine. A pulse air system is, of course, much less expensive than an air pump.

TABLE 9. PULSAIR FLOW RATES EXPRESSED AS PERCENTAGE OF ENGINE AIRFLOW

Engine Condition	Engine Speed, rpm	Intake Manifold Vacuum, in. Hg.	Percentage of Engine Airflow
Idle	600	16	60
Mid-speed cruise	1200	16	45
High-speed accel	2200	6	10

(5) Improved Open Loop Carburetor

Manufacturers of M11 category equipment have stated that they use the least expensive carburetor possible in order to be cost competitive. With better fuel control, it should be possible to run engines less rich, and achieve some of the emission benefits discussed above under the heading, "Air-Fuel Ratio."

(6) Oxidation or Three-way Catalytic Converter

A variety of automotive-type catalysts are commercially available for engines in the M11 category. Indeed, a number of individual end-users have installed catalysts on equipment such as forklifts, to meet various indoor requirements for air quality. Catalyst performance depends on exhaust gas temperature, catalyst noble metal loading, and catalyst size relative to exhaust gas flowrate. The type of catalytic noble metal used also affects performance. Cost is a function of noble metal type and loading, catalyst size, and of course, sales volume.

The type of catalytic action also needs to be considered. Automotive catalysts were initially only oxidation catalysts, reducing HC and CO. To accomplish this, air was injected into the engine exhaust. Platinum and palladium were the noble metals used in these catalysts. While these systems reduced HC and CO, they had little effect on NO_x.

Current three-way automotive technology uses catalysts that also control NO_x using the reactions:

$$2NO + 2CO \rightarrow N_2 + 2CO_2$$

$$2NO + 2H_2 \rightarrow N_2 + 2H_2O$$

$$[2 + (n/2)]NO + C_yH_n \rightarrow [1 + (n/4)]N_2 + yCO_2 + (n/2)H_2O$$

For these reactions to occur, however, the engine must be controlled to slightly rich of stoichiometric. Current automobile engines actually perturbate the A/F ratio about stoichiometric, and use additional materials (generally ceria) to store oxygen and NO, so that conditions in the catalyst exist for both the oxidation of HC and CO, and the reduction of NO. Since such catalysts control HC, CO, and NO_x, they are called three-way catalysts.

Rhodium is generally used as the catalytic noble metal to promote NO_x reduction. The addition of rhodium, which is much less abundant than platinum, and therefore more expensive, adds to the cost of the three-way catalyst.

Over the past eight to ten years, a number of catalyst companies have investigated using palladium-only three-way catalysts. Palladium is much cheaper than either platinum or rhodium. Using palladium-only catalysts to obtain the reductions in emissions required by passenger car LEV and ULEV standards requires relatively high exhaust temperatures and very tight A/F ratio control.

(7) Summary of Emission Reductions from Lower Cost Technologies

Table 10 summarizes the estimated reductions possible with each of the emission control methods discussed above. While none of the methods can meet the M11 emission reduction requirements alone (with the possible exception of a catalyst system), a number of possible combinations can be envisioned which could provide respectable emission control. Table 11 lists several combinations of methods together with the estimated total HC and NO_x reductions that might be achievable. Note that none of these systems comes close to meeting the reductions required by the SIP, therefore SwRI did not recommend any of these systems for use as a second control system for this project.

TABLE 10. ESTIMATED EMISSION REDUCTIONS OBTAINABLE WITH VARIOUS CONTROL METHODS

Method	Estimated Percent Change Obtainable		Remarks
	HC	NOx	
Calibration			
A/F enleanment toward stoichiometric	-10	+10	also lowers fuel consumption
Spark retard (10 to 20 degrees)	-30	-35	increases fuel consumption 20 percent or more
Other Methods			
EGR (15% of inlet flow)	none	-50	
Air injection into exhaust ports	-30 to -50	none	
Improved open loop carburetor			Required for calibration, EGR and catalyst reductions
Low Cost Catalyst			
Oxidation	-60 to -80	none	with open loop carburetion and air injection
Three-way	-50 to -70	-50	with open loop carburetion, no air injection

TABLE 11. SUGGESTED COMBINATIONS OF EMISSION CONTROL METHODS

Combination	Estimated Total Percent Reduction		Remarks
	HC	NOx	
Spark retard	30	35	Least cost system. As much as 20 % fuel consumption increase, however.
Modest spark retard, A/F enleanment, high EGR rate, improved carburetor	30	60	EGR valve and improved carburetor are added cost components.
Modest spark retard, A/F enleanment, high EGR rate, improved carburetor, pulse air injection system.	60	60	EGR valve, improved carburetor, and pulse air system are added cost components.
Modest spark retard, A/F enleanment, high EGR rate, improved carburetor, pulse air injection system, low cost oxidation catalyst.	80	60	EGR valve, improved carburetor, pulse air system, and oxidation catalyst are added cost components

3. Technical Advisory Committee

A Technical Advisory Committee (TAC) was formed with representatives from equipment, engine, fuel system, and catalyst manufacturers, and industry associations. The purpose of the TAC was to provide technical information and support to specific project tasks.

a. TAC Meetings

The first meeting of the TAC was held at SwRI in San Antonio, Texas, on May 15, 1997. The organizations represented and their representatives in attendance were:

Ford Power Products/EMA - Jim Hudzinski
ITA - Gary Cross
NACCO - Bob Downey, Rick Steele
Nissan - George Maes
WIS-CON - Jerome Berti
MECA - Dale McKinnon
ASEC - John Howitt
Zenith - Jim Gorny
IMPCO - Bob Burrahm
Algas - Roger Shugart
CARB - Nancy Steele
SwRI - Mel Ingalls, Jim Carroll, and Jeff White

The following eight topics were discussed by the committee at the first meeting:

- Category equipment population and sales
- Emission reduction technology development and manufacturing issues
- Typical operating modes for off-road equipment
- Recommendations regarding test cycles and procedures
- Emission reduction technology costs
- Procurement of five program engines
- Engines and fuel types for system demonstrations
- Support for system development and durability testing.

A second meeting of the TAC committee was held on September 25, 1997, at SwRI. The organizations represented and their representatives in attendance were:

Ford Power Products - Jim Hudzinski
ITA - Gary Cross
NACCO - Rick Steele
EMA - Kate Drakos
GM - Chuck Elder
SwRI - Mel Ingalls, Jim Carroll, and Jeff White

Three topics were discussed during this meeting:

- Recommendations regarding test cycles
- Project test schedule
- Cost analysis methodology.

b. <u>TAC Contributions</u>

The discussions for each topic are presented in the sections that follow.

(1) Equipment Population and Sales

Discussions focused on the characteristics of engines and equipment in this category, and on the quality of the currently available population data. It was noted that the Booz-Allen and Hamilton inventory does not include a category for LPG generator sets, although there are a number of these in California. CARB is working on a revised inventory (EEA) for this category, which is expected to be more accurate than the Booz-Allen inventory which is likely based on 1989 or 1990 data. CARB later directed us to use the EEA inventory data for this project. Although SIP measures M11 and M12 do not address CNG-fueled engines, we were advised that CARB's regulation is expected to include these types of engines.

(2) Emission Reduction Technology Development and Manufacturing Issues

Both carburetors and fuel injection systems are in use on category equipment. NACCO is selling a number of fuel injected lift trucks although Nissan plans to continue to use carburetors. Ford supplies both carbureted and fuel injected engines.

Forklift engine technologies must be designed around the size limits of the engine compartments. Compartment temperatures are a concern for heat sensitive components. The Manufacturers of Emission Controls Association (MECA) commented that catalysts have been successfully applied in lift truck mufflers installed inside the engine compartment. MECA reported that well over 100,000 catalyst systems have been sold to the industrial lift truck market. While most of these are two-way systems, over 1,000 three-way systems have been more recently installed. Several models have received UL recognition, and these can be used by an OEM in a piece of equipment being evaluated for UL recognition without requiring retesting of the muffler.

MECA stated that the two-way systems are designed to reduce CO and HC emissions with efficiencies of greater than 90 percent. These systems have been in the marketplace for over 20 years. To protect the catalyst from overheating, a temperature alarm is typically installed, which alerts the operator if excessive temperatures occur. In such cases, a carburetor adjustment is recommended to correct the problem. MECA stated that the large majority of systems are the muffler replacement type.

In the last few years, three-way catalyst systems have been introduced into the industrial truck marketplace. Like two-way systems, these can be either a direct in-line fit, or a muffler replacement. Again, muffler replacement systems currently constitute the majority of sales. A controller is sold with the catalyst to control carburetion near stoichiometric. MECA reported that eight-mode test data on one application showed NO_x emissions of 1.1 g/hp-hr, with CO and HC emissions of 0.78 and 0.04 g/hp-hr, respectively. In an on-going demonstration of 44 lift trucks, decreases of only about five percent NO_x and CO performance have been measured after 4,000 to 6,000 hours of operation. Data obtained indicates that the systems are durable and maintain good emission reduction performance over extended periods of time.

(3) Typical Operating Modes for Off-Road Equipment

Forklifts

ITA favors the use of the seven-mode ISO 8178-C2 cycle, which was modified in 1993 to better model lift truck operation. NAACO presented an analysis of data based on lift truck operation using the MIL - 268C cycle, which is a fork lift vehicle qualification cycle including turns and lifting operations. NAACO's analysis suggests that the C2 cycle is more highly loaded than typical lift truck operation.

Lift truck operation varies between commercial use and lighter ("mom and pop") use. Commercial users may start the truck at the beginning of the work day, and not shut the engine off, allowing it to idle during intervals between jobs. With lighter usage, the lift truck is started up for each job, and could be restarted many times during a day. Nissan commented that 30 percent of their sales were to commercial users, and 70 percent were to lighter users; but that the commercial service involved several times the amount (hours) of lift truck usage, compared to "mom and pop" usage.

Aircraft Ground Power

Aircraft ground power is essentially generator operation which is well modeled by the five-mode ISO 8178-D2 cycle. Ford commented than 45 to 60 minutes of operation between engine starts is typical.

Baggage Handling

Baggage handling equipment has two modes of operation–driving between aircraft, and running at high idle (~10% load) to convey baggage into aircraft baggage compartments. Ford commented that in Detroit during the winter, the equipment is left running all day, but that during the summer the equipment is shut off between jobs. Ford commented it was unclear whether the C2 cycle fit baggage handling.

Tow/Push

Ford commented that tow/push equipment for large aircraft is diesel powered. Smaller aircraft tugs are also used to move baggage. The six cylinder 4.9L Ford engine is used in many of these applications. Tow/push service is not well modeled by the C2 cycle.

Generator Sets

Generator sets are typically started and left on through long periods of use. Generator set operation is well modeled by the D2 cycle.

Scrubbers/Sweepers

Ford commented that this equipment is usually run for long periods of time, such as a work shift. It is a lightly loaded application, and is considered reasonably modeled by the C2 cycle.

Turf Care Equipment

This equipment is usually operated for long periods of time, such as a work shift. The C2 cycle is considered a good fit for the application.

Specialty Vehicles

This category is understood to be people movers (trams). This type of equipment is usually operated for long periods of time and is well modeled by the C2 cycle.

Mining Equipment, Surface

The consensus of the TAC was that this is all diesel powered.

Refrigeration Units, <50hp

This type of equipment is operated continuously much like a genset, and is well modeled by the D2 cycle. It was noted that most of these units are diesel fueled, but some are LPG fueled.

Other Industrial Equipment

This subcategory includes Zamboni ice machines, airplane washers, airport (nonhighway) trucks, and other equipment.

(4) Recommendations Regarding Test Cycles and Procedures

Very little data is available that characterizes category equipment operation. Data that is available and TAC member experience suggests that much of the equipment in this category is well modeled by the ISO 8178 C2 or D2 cycles. Much equipment is operated for long periods of time with infrequent cold- or hot-starts, although some forklifts and airport service equipment may be frequently stopped and restarted. Equipment such as generators, pumps, and refrigeration units runs in steady-state operation, but most other equipment in this category has vehicle-like transient operating characteristics with varying engine speeds and loads. Clearly, forklifts, baggage handling equipment, scrubbers and sweepers, turf care equipment, and specialty vehicle operation would be most accurately represented using some type of transient cycle, although it would be difficult to design one cycle that would be considered representative of these diverse applications. Additionally, a study would first need to be done to properly characterize the operation of these equipment types as a basis for cycle development. Until such data are available, a steady-state cycle may need to be used to certify this type of equipment. While the C2 cycle does not fit any of the applications perfectly, it is supported by ITA and EMA as appropriate for this equipment.

(5) Emission Reduction Technology Costs

MECA and ITA both offered technology cost information. A category California market of 15,000 units per year (10% of federal market) was assumed. UL certification was estimated to cost $30,000. It was agreed that the cost of emission certification should be included in the cost analysis.

(6) Procurement of Five Program Engines

Engines were offered for use in the program by a number of manufacturers. Zenith and two other manufacturers offered to assist with fuel systems. Both MECA and ASEC offered to supply catalysts.

CARB agreed that each manufacturer could be provided with a copy of the data from its engine, in consideration for loaning engines to the program. CARB also agreed that the engines could be coded to keep manufacturer identification confidential.

(7) Engines and Fuel Types for System Demonstrations

The U.S. EPA inquired about consideration of a "no catalyst" technology which could achieve lower emissions through the use of, for example, a fuel injection system. Three points were made relative to this proposal.

- No specific examples could be identified of an engine that could not utilize a catalyst.
- The "low cost" system needs to be able to work on an engine without an electrical system.
- Both systems need to meet project/SIP goals, and fuel injection by itself will not provide this.

(8) Support for System Development and Durability Testing

TAC members stressed the need for an on-site champion for these demonstrations to be successful. They also provided many examples of how equipment operators may, intentionally or unintentionally, disable or sabotage a system they don't like. While in-use applications will provide the most real-world demonstration of these systems, there is a much greater likelihood of a failed experiment than if done under more controlled conditions. The use of a data logger was recommended to track basic operating parameters.

B. <u>Task 1.2 - Technical Feasibility of Proposed Emission Standards</u>

1. Emissions Reductions Required

The first item of work for this task was to determine the individual engine emission reductions required using the SIP information. This was done based on tons per day information in the SIP, and the South Coast Air Basin (SCAB) equipment inventories provided by ARB's Mobile Source Division, Inventory Assessments Section.

The SIP uses the year 2010 as the date for compliance with ambient air standards, and assumes that the regulations for this equipment category will be in place for model year 2000. The individual engine emission reductions can be calculated from the SIP category baseline emissions (tons/day) in 2010, the required category emissions (tons/day) to meet the SIP goals in 2010, and the age distribution of the equipment in the category in 2010.

The SIP has two tables in the section that discusses M11. One table shows the estimated SCAB emission inventory for this category in 1990 and 2010 for the current situation of no controls (baseline). The second table shows the emissions reductions required in the SCAB by various dates in order to meet SIP ambient air quality goals. Table 12 combines the two SIP tables into one. In addition, the presumed emission inventory required (simply the difference between the inventory and the required reduction) to meet the SIP goals in 2010 is also shown.

TABLE 12. SIP EMISSIONS IN THE SOUTH COAST AIR BASIN

	ROG/NOx Emissions, tons per day in year					
	1990	1999	2002	2005	2007	2010
Baseline	42/27					63/42
Reduction required	0/0	0/0	10/6	22/12	34/18	48/24
Net into air	42/27					15/18

Ms. Archana Agrawal, Manager, Inventory Assessments Section of the ARB Mobile Source Division in El Monte, was contacted regarding information on the age distribution of equipment in this category. Her staff provided a population table by year, from which was calculated an age distribution for this category. This information is presented here as Table 13. The information provided had negative population in years 19 and 20, due to an anomaly in the model algorithm. Therefore, it was necessary to estimate the population in years 17 to 20 by smoothing a graph of the population by year. This procedure has only a minor effect on the calculations of emissions reductions required. Note that percent values do not total exactly 100.00 percent because of rounding.

TABLE 13. M11 CATEGORY SOUTH COAST AIR BASIN REGISTRATION DISTRIBUTION (APPLIES TO ALL HP CATEGORIES)

Age	Percent of Total in Service in 2010	Age	Percent of Total in Service in 2010
0	9.24	17	1.24
1	17.10	18	0.83
2	12.71	19	0.66
3	7.44	20	0.55
4	5.70	21	0.48
5	5.61	22	0.45
6	5.28	23	0.33
7	4.55	24	0.28
8	3.85	25	0.25
9	3.32	26	0.19
10	3.20	27	0.14
11	3.27	28	0.11
12	3.13	29	0.08
13	3.00	30	0.05
14	2.79	31	0.03
15	2.55	32	0.02
16	1.60		

From the information in Table 13, it can be calculated that in 2010, 78 percent of the equipment in this category will be emission controlled to a year 2000 standard, and that 22 percent of the equipment will be uncontrolled. For the M11 category to meet the SIP goals in 2010, the following equation must be satisfied:

$$TE = 0.78 \times P \times Ec + 0.22 \times P \times Eb \quad (1)$$

Where:

TE = total exhaust emissions from category, tons/day
P = equipment population in 2010
Ec = average controlled individual engine emission rate, tons/day
Eb = average baseline individual engine emission rate, tons/day

Dividing this equation by P×Eb:

$$TE/PEb = 0.78(Ec/Eb) + 0.22$$

Solving for (Ec/Eb):

$$Ec/Eb = (TE/PEb - 0.22)/0.78 \quad (2)$$

From Table 12, to meet the 2010 SIP goals, the category can only produce 15 tons/day of ROG in the SCAB in 2010, and 18 tons/day of NO_x. Thus:

TE = 15 for ROG
TE = 18 for NO_x

From the baseline case for 2010 shown in Table 12, the following equations apply for ROG and NO_x:

$P \times Eb = 63$ for ROG
$P \times Eb = 42$ for NO_x

Substituting these values for ROG and NO_x into equation (2)

For ROG: $Ec/Eb = (15/63 - 0.22)/0.78 = 0.0232$
For NO_x: $Ec/Eb = (18/42 - 0.22)/0.78 = 0.2674$

Thus, the controlled individual equipment emission rate (i.e the emission standard) must be 2.32 percent of the uncontrolled (baseline) emissions for ROG, and 26.7 percent of the uncontrolled emissions for NO_x. This means that, for individual equipment emissions, there must be a 97.7 percent reduction in ROG, and a 73.3 percent reduction in NO_x to meet SIP goals.

If the emission standards become effective in some other model year, similar calculations can be made. The reductions required for the years 2000 to 2004 are shown in Table 14, indicating that if the standards become effective in any year after 2000, the SIP emission reduction goals for ROG cannot be met in 2010.

TABLE 14. INDIVIDUAL ENGINE REDUCTIONS REQUIRED TO MEET SIP GOALS IN 2010 FOR EMISSION STANDARDS INTRODUCTION IN THE YEARS 2000 TO 2004

Year Standards Introduced	Individual Engine Emission Reductions Required, %	
	ROG	NO_x
2000	97.7	73.3
2001	>100	76.4
2002	>100	80.0
2003	>100	84.5
2004	>100	90.6

2. Recommended Test Procedures

Test cycles recommended at the May 15, 1997 TAC meeting were:

ISO 8178-C2 cycle	Variable speed applications such as forklifts, baggage handling and tow/push equipment, scrubbers/sweepers, turf care equipment, and specialty vehicles
ISO 8178-D2 cycle	Constant speed applications such as generator sets, aircraft ground power, and refrigeration units

ISO 8178 CYCLE C2
LOWER LOADED APPLICATIONS - FORK LIFTS, AIRPORT SERVICE EQUIPMENT

Mode No.	1	2	3	4	5	6	7
Speed	Rated	Intermediate					Low idle
Torque, %	25	100	75	50	25	10	0
Wt. Factor	0.06	0.02	0.05	0.32	0.3	0.1	0.15

ISO 8178 CYCLE D2
RATED SPEED, HIGHER LOADED APPLICATIONS - GENERATORS

Mode No.	1	2	3	4	5
Speed	Rated				
Torque, %	100	75	50	25	10
Wt. Factor	0.05	0.25	0.3	0.3	0.1

NACCO proposed a revised cycle based on analysis of data from lift truck operation using the Mil-Std-268C test course. NACCO argued that their proposed cycle (shown below) modeled lift truck operation much better than the C2 cycle.

NACCO PROPOSAL FOR SI LIFT TRUCK ENGINES

Mode No.	1	2	3	4	5	6
Speed	Intermediate (50% Governed Speed)					Low Idle
Torque, %	100	75	50	25	10	0
Wt. Factor	0.02	0.05	0.28	0.3	0.1	0.25

Following the TAC meeting, the proposed cycle was further evaluated by other ITA members, and a copy of the NAACO proposal was also forwarded to EMA. While the proposal had merit, it did not receive much support from others. Issues included:

- not unanimously supported by other ITA members
- not broadly reviewed by others
- initial comments from EMA not favorable
- impact on emission results unknown
- concern about impact on existing C2 database
- unclear whether it well represents a broader class of equipment than just fork lifts

Also, the weight factors in the NACCO proposed cycle are different than the Mil-Std. course data. The following table shows mode speeds, torques, and weight factors, as derived from table "Hyster 1983 Test Data," in NACCO's Oct. 14, 1996 letter (revised May 30, 1997) to Mr. Gary Cross. Weight factors in modes 3, 5, and 6 of the proposed cycle have been adjusted from course data, confirming that experience factors also play a role in test cycle definition.

NACCO MIL-STD-268C COURSE DATA

Mode No.	1	2	3	4	5	6
Speed, % gov	55	51	51	54	49	Low Idle
Torque, %	92	74	50	26	8	0
Wt. Factor	0.02	0.04	0.17	0.26	0.19	0.32

A significant aspect of the NACCO proposal involves revision of test speed definitions. NACCO's data clearly show that lift truck engines operate primarily around 50% of engine governed speed. It could be possible to significantly improve the fit of the existing C2 cycle by modifying test cycle speed definitions, as follows:

- Declaring rated speed as governed speed for testing purposes

  This is allowed as terms are defined in the ISO procedure.

- Declaring intermediate speed as 50% of governed speed

  ISO procedure 8178 clause 6.1 defines intermediate speed as the speed at which peak torque occurs between 60 and 75% of rated speed. ISO procedure clause 6.4 allows a different definition of intermediate speed for utility engines (85% of rated speed). A revised definition could be added to the ISO 8178 procedure, stating that intermediate speed for the C2 cycle is the speed declared by the manufacturer between 50 and 75% of rated speed.

NACCO was contacted for clarification regarding its recommendations to change the ISO-8178-C2 test cycle. NACCO was unable to define how to test their engines with the governor operational, without testing each type of governor installed on each engine. NACCO's position was that testing all the governors reflects real world operation. NACCO responded to our question of how to test an engine at governed speed, with the governor operational and limiting power, by saying that there would be power available during laboratory testing because auxiliary equipment power losses would be removed. NACCO explained that their governors are adjusted on the lift truck at the end of the production line, and that the hydraulic pump, alternator, and fan load the engine enough that the governor will allow higher engine speed when these loads are removed. Once auxiliary loads are removed, the maximum measured power (still partially governed) available at governed speed would then become the rated power, and 25 percent of this measured power would be the Mode 1 set point for the C2 test cycle.

SwRI believes that emission testing with the governor operational would cause highly variable results, and that no manufacturers, including NACCO, will rate engine power based on governed operation. In addition, testing all governors applied on each engine model or family would cause an undue testing burden on engine manufacturers. In subsequent telephone conversations with a few of the TAC members regarding NACCO's proposed changes to the C2 cycle, we found that <u>only</u> NACCO supports the changes. Other manufacturers were not interested in the suggested broadened intermediate speed definition. For these reasons, we recommend that all non-fixed-speed spark-ignited industrial engines which produce greater than 25 hp, be tested with their governor disabled or removed; and we withdraw our earlier proposal to allow intermediate speed to be defined as low as 50 percent of rated speed. Engine manufacturers will still be free to define engine rated speed, as appropriate.

In summary, SwRI recommends using the ISO 8178-C2 cycle for variable speed applications, and the ISO 8178-D2 cycle for constant speed applications, as written without modification.

3. Recommended Emission Standards

Emission standards recommended are calculated to meet the SIP goals for ROG and NO_x reduction. These standards are based on the percent emission reduction required for individual engines, calculated in Section II.B.1 above, and average baseline emission levels, based on results from this project and selected data from previous projects which used the same test cycles. One standard is recommended even though two test cycles are used.

a. Standards for THC and NO_x

Average baseline emissions for engines tested using the ISO 8178-C2 and D2 cycles are given in Section III.A of this report. In addition to data in this project, the C2 test cycle was used on several engines in previous projects. A summary of available emissions data using these cycles on engines in the M11 category is given in Table 15.

TABLE 15. SUMMARY OF M11 EMISSION DATA USING ISO 8178-C2 AND D2 CYCLES

Engine	Test Cycle	Fuel	Emissions, g/hp-hr			Remarks
			HC	CO	NOx	
A	C2	Gasoline	1.69	20.1	12.0	Average of two tests (This project)
B	C2	Gasoline	1.49	16.3	8.3	Average of two tests (This project)
B	C2	LPG	0.94	7.37	11.7	Average of two tests (This project)
C	C2	Gasoline	3.81	50.7	7.7	Average of two tests (This project)
C	C2	LPG	1.70	8.8	11.5	Average of two tests (This project)
D	C2	Gasoline	3.99	124	5.4	Average of two tests (This project)
D	D2	LPG	0.89	2.1	9.9	Average of two tests (This project)
E	C2	Gasoline	18.7	684	1.1	Average of two tests (This project)
E	D2	Gasoline	10.7	479	1.7	Average of two tests (This project)
40 HP Lift Truck	C2	LPG	1.17	5.74	13.8	Average of two tests (ARB contract A198-076) [7]
F	C2	Gasoline	3.23	49.9	13.7	Avg. of 3 different carburetors
F	C2	LPG	2.90	141	4.93	One test
G	C2	LPG	2.28	27.3	15.4	Two tests. Fuel system "x" (Texas Railroad Com. project) [8]
G	C2	LPG	1.88	5.32	16.73	Two tests. Fuel system "y" (Texas Railroad Com. project) [8]
Average (all results)			3.96	115.8	9.56	
Average (excluding E)			2.16	38.2	10.92	

From the above table (all results average) and the required percent reductions calculated for individual engines, the recommended HC and NO_x standards are calculated as follows:

(Average g/hp-hr) x (1-percent reduction/100) = Recommended standard

For HC: (3.96 g/hp-hr) × (0.023) = 0.09 g/hp-hr
For NO_x: (9.56 g/hp-hr) × (0.267) = 2.55 g/hp-hr

In discussions with ARB staff during the course of this project, SwRI was asked to estimate what levels technically feasible standards would be, based on current technology. Table 7, in Section II.A.2.a, lists emissions results actually obtained on engines in this category using automotive three-way catalyst technology. Those results showed an average 90 percent reduction for HC and a 77 percent reduction for NO_x. Using these emission reductions and the average baseline results for all engines in Table 15, technologically feasible standards are:

For HC: (3.96 g/hp-hr) × (0.1) = 0.40 g/hp-hr
For NO_x: (9.56 g/hp-hr) × (0.23) = 2.20 g/hp-hr

Note that the technologically feasible standard for HC is above the standard level calculated to be needed to meet the SIP reductions, but the technologically feasible NO_x standard is actually lower than the standard needed to meet the SIP reductions. Also note that these values are based on *average* percent reductions from Table 7, and that greater reductions have been reported for specific, well developed applications.

b. Carbon Monoxide Standards

Carbon monoxide (CO) reductions were not part of the M11 strategy. For estimation of emission factors of controlled engines, a CO reduction of 95 percent was assumed, based on emission reductions observed on off-road engines fitted with three-way catalysts and closed-loop control systems, as reported in Section II.A.2.a.

C. Task 1.3 - Cost Effectiveness Analysis

Based on the recommended standards and the engine baseline emissions, the emission reductions needed per engine to meet those standards were calculated. Using these values and the cost of the emission control systems necessary to obtain these emission reductions, the cost effectiveness of these standards was calculated in dollars per pound of emission reduction.

1. Population and Usage

The information needed to calculate both incremental per engine costs and average per engine emission reductions is dependent on the category population (total and equipment type) and the usage characteristics (average and equipment type). This section presents category population and usage characteristics as obtained from the ARB off-road equipment emissions inventory model.[17] Estimates were developed separately for both non-preempted equipment (control category M11 in the California SIP), and for preempted equipment (control category M12 in the California SIP).

a. Population

The basis for the cost-effectiveness analysis is population and usage data obtained from the ARB in early 1998. This population information is different than that given elsewhere in this report, because these data are from later ARB estimates of the category population.

Preempted and non-preempted equipment were separated based on notes ARB provided with the data set. The total 2010 California population of this equipment category, including both non-preempted and preempted equipment, is listed below in Table 16. Table 17 presents 2010 non-preempted California equipment population and usage data, and Table 18 presents 2010 preempted equipment data.

TABLE 16. CALIFORNIA STATEWIDE POPULATION OF INDUSTRIAL EQUIPMENT

	2010 Population
Non-preempted	29,720
Preempted	53,326
Total	83,046

TABLE 17. NON-PREEMPTED POPULATION AND USAGE BY EQUIPMENT TYPE

Category	ASC Code	Description	Fuel[a]	HP Class[b]	Statewide 2010 Pop.	Act.[c]	Avg. HP	Life	Load	BSFC[d]
Light-duty Industrial	2265003020	Forklifts	G4	50	1376	1800	41	3	0.3	0.7
Light-duty Industrial	2265003030	Sweepers/Scrubbers	G4	50	909	516	35	3	0.71	0.7
Light-duty Industrial	2265003030	Sweepers/Scrubbers	G4	120	759	516	68	16	0.71	0.55
Light-duty Industrial	2265003030	Sweepers/Scrubbers	G4	175	4	516	140	1	0.71	0.55
Light-duty Industrial	2265003040	Other General Industrial	G4	50	311	713	30	4	0.54	0.7
Light-duty Industrial	2265003040	Other General Industrial	G4	120	102	713	79	4	0.54	0.55
Light-duty Industrial	2265003040	Other General Industrial	G4	175	10	713	174	3	0.54	0.55
Light-duty Industrial	2265003050	Other Material Handling	G4	50	4	386	41	6	0.53	0.7
Light-duty Industrial	2265003050	Other Material Handling	G4	120	195	386	54	16	0.53	0.55
Agricultural	2265005020	Combines	G4	250	23	125	194	16	0.74	0.55
Agricultural	2265005055	Other Agricultural	G4	250	25	124	246	10	0.55	0.55
Light-duty Commercial	2265006005	Generator Sets	G4	50	14925	115	32	16	0.68	0.7
Light-duty Commercial	2265006005	Generator Sets	G4	120	2882	115	83	16	0.68	0.55
Light-duty Commercial	2265006005	Generator Sets	G4	175	272	115	146	16	0.68	0.55
Airport Ground Support	2265008015	A/C Tug, Narrow Body	G4	175	61	551	130	7	0.8	0.55
Airport Ground Support	2265008020	A/C Tug, Wide Body	G4	500	24	515	500	7	0.8	0.55
Airport Ground Support	2265008025	Air Conditioner	G4	175	0	22	130	16	0.75	0.55
Airport Ground Support	2265008030	Air Start Unit	G4	175	0	135	130	16	0.9	0.55
Airport Ground Support	2265008035	Baggage Tug	G4	120	912	876	100	6	0.55	0.55
Airport Ground Support	2265008040	Belt Loader	G4	120	430	810	60	7	0.5	0.55
Airport Ground Support	2265008045	Bobtail	G4	120	130	876	100	6	0.55	0.55
Airport Ground Support	2265008050	Cargo Loader	G4	120	131	719	70	8	0.5	0.55
Airport Ground Support	2265008060	Deicer	G4	120	40	22	93	16	0.95	0.55
Airport Ground Support	2265008065	Forklift	G4	50	124	726	50	6	0.3	0.7
Airport Ground Support	2265008070	Fuel Truck	G4	175	79	22	130	16	0.25	0.55
Airport Ground Support	2265008075	Ground Power Unit	G4	175	101	796	150	5	0.75	0.55
Airport Ground Support	2265008085	Lav Truck	G4	175	100	1212	130	9	0.25	0.55
Airport Ground Support	2265008090	Lift	G4	120	198	376	100	16	0.5	0.55
Airport Ground Support	2265008095	Maint. Truck	G4	175	137	449	130	13	0.5	0.55
Airport Ground Support	2265008100	Other	G4	50	226	183	50	16	0.5	0.7
Airport Ground Support	2265008105	Service Truck	G4	250	235	1299	180	11	0.2	0.55
Airport Ground Support	2265008110	Water Truck	G4	175	31	310	150	16	0.2	0.55
Light-duty Industrial	2266003020	Forklifts	C4	50	4034	1800	41	3	0.3	0.55
Light-duty Commercial	2266006005	Generator Sets	C4	120	215	115	83	16	0.68	0.55
Light-duty Commercial	2266006005	Generator Sets	C4	175	178	115	146	16	0.68	0.55
Airport Ground Support	2266008025	Air Conditioner	C4	175	7	22	130	16	0.75	0.55
Airport Ground Support	2266008035	Baggage Tug	C4	120	126	876	100	6	0.55	0.55
Airport Ground Support	2266008040	Belt Loader	C4	120	27	810	60	7	0.5	0.55
Airport Ground Support	2266008045	Bobtail	C4	120	3	6	100	6	0.55	0.55
Airport Ground Support	2266008050	Cargo Loader	C4	120	7	8	70	8	0.5	0.55
Airport Ground Support	2266008065	Forklift	C4	50	289	6	50	6	0.3	0.55
Airport Ground Support	2266008085	Lav Truck	C4	175	3	9	130	9	0.25	0.55
Airport Ground Support	2266008090	Lift	C4	120	8	376	100	16	0.5	0.55
Airport Ground Support	2266008100	Other	C4	50	25	16	50	16	0.5	0.55
Airport Ground Support	2266008105	Service Truck	C4	250	42	11	180	11	0.2	0.55
Total					29720					

[a] Fuel Type: C4 = LPG or CNG (4-stroke), G4 = gasoline (4-stroke)
[b] HP Class = Upper boundary of HP range
[c] Activity, hours per year
[d] BSFC, lbs/hp-hr

TABLE 18. PREEMPTED POPULATION AND USAGE BY EQUIPMENT TYPE

Category	ASC Code	Description	Fuel[a]	HP Class[b]	Statewide 2010 Pop.	Act.[c]	Avg. HP	Life	Load	BSFC[d]
Agricultural	2265005015	Agricultural Tractors	G4	120	946	550	82	16	0.62	0.55
Agricultural	2265005015	Agricultural Tractors	G4	175	129	550	125	16	0.62	0.55
Agricultural	2265005020	Combines	G4	120	237	125	103	9	0.74	0.55
Agricultural	2265005020	Combines	G4	175	132	125	164	10	0.74	0.55
Agricultural	2265005025	Balers	G4	50	3453	68	35	16	0.55	0.7
Agricultural	2265005025	Balers	G4	120	1765	68	75	16	0.55	0.55
Agricultural	2265005035	Sprayers	G4	50	650	80	33	16	0.5	0.7
Agricultural	2265005035	Sprayers	G4	120	1094	80	68	12	0.5	0.55
Agricultural	2265005035	Sprayers	G4	175	246	80	140	16	0.5	0.55
Agricultural	2265005045	Swathers	G4	120	3540	95	88	16	0.52	0.55
Agricultural	2265005045	Swathers	G4	175	2712	95	129	12	0.52	0.55
Agricultural	2265005050	Hydro Power Units	G4	50	33	450	38	5	0.56	0.7
Agricultural	2265005050	Hydro Power Units	G4	120	4	450	66	3	0.56	0.55
Agricultural	2265005055	Other Agricultural	G4	50	107	124	29	16	0.55	0.7
Agricultural	2265005055	Other Agricultural	G4	120	621	124	67	15	0.55	0.55
Agricultural	2265005055	Other Agricultural	G4	175	71	124	136	9	0.55	0.55
Construction	2265002003	Asphalt Pavers	G4	50	139	392	32	5	0.66	0.7
Construction	2265002003	Asphalt Pavers	G4	120	76	392	61	16	0.66	0.55
Construction	2265002015	Rollers	G4	50	96	621	37	16	0.62	0.7
Construction	2265002015	Rollers	G4	120	183	621	75	16	0.62	0.55
Construction	2265002021	Paving Equipment	G4	50	376	175	37	13	0.59	0.7
Construction	2265002021	Paving Equipment	G4	120	96	175	66	8	0.59	0.55
Construction	2265002030	Trenchers	G4	50	884	402	30	5	0.66	0.7
Construction	2265002030	Trenchers	G4	120	293	402	66	16	0.66	0.55
Construction	2265002033	Bore/Drill Rigs	G4	50	42	107	32	16	0.79	0.7
Construction	2265002033	Bore/Drill Rigs	G4	120	196	107	88	16	0.79	0.55
Construction	2265002033	Bore/Drill Rigs	G4	175	48	107	126	16	0.79	0.55
Construction	2265002039	Concrete/Industrial Saws	G4	50	160	610	35	3	0.78	0.7
Construction	2265002039	Concrete/Industrial Saws	G4	120	90	610	66	2	0.78	0.55
Construction	2265002045	Cranes	G4	50	48	415	37	6	0.47	0.7
Construction	2265002045	Cranes	G4	120	97	415	74	16	0.47	0.55
Construction	2265002045	Cranes	G4	175	3	415	125	16	0.47	0.55
Construction	2265002054	Crushing/Proc.	G4	120	56	241	96	16	0.85	0.55
Construction	2265002057	Rough Terrain Forklifts	G4	50	20	413	47	4	0.63	0.7
Construction	2265002057	Rough Terrain Forklifts	G4	120	275	413	85	16	0.63	0.55
Construction	2265002057	Rough Terrain Forklifts	G4	175	10	413	142	3	0.63	0.55
Construction	2265002060	Rubber Tired Loaders	G4	50	48	512	40	3	0.54	0.7
Construction	2265002060	Rubber Tired Loaders	G4	120	322	512	72	4	0.54	0.55
Construction	2265002066	Tractors/Loaders/Backhoes	G4	120	172	870	63	16	0.48	0.55
Construction	2265002072	Skid Steer Loaders	G4	50	1326	310	32	10	0.58	0.7
Construction	2265002072	Skid Steer Loaders	G4	120	794	310	80	10	0.58	0.55
Construction	2265002078	Dumpers/Tenders	G4	120	35	127	66	16	0.41	0.55
Construction	2265002081	Other Construction	G4	175	136	371	126	6	0.48	0.55

TABLE 18 (CONT'D). PREEMPTED POPULATION AND USAGE BY EQUIPMENT TYPE

Category	ASC Code	Description	Fuel[a]	HP Class[b]	Statewide 2010 Pop.	Act.[c]	Avg. HP	Life	Load	BSFC[d]
Light-duty Commercial	2265006010	Pumps	G4	50	1193	221	93	10	0.69	0.55
Light-duty Commercial	2265006010	Pumps	G4	120	1511	221	144	16	0.69	0.55
Light-duty Commercial	2265006010	Pumps	G4	175	45	221	31	16	0.69	0.7
Light-duty Commercial	2265006015	Air Compressors	G4	50	453	484	35	5	0.56	0.7
Light-duty Commercial	2265006015	Air Compressors	G4	120	1470	484	70	16	0.56	0.55
Light-duty Commercial	2265006015	Air Compressors	G4	175	99	484	134	4	0.56	0.55
Light-duty Commercial	2265006025	Welders	G4	50	2370	208	130	10	0.51	0.55
Light-duty Commercial	2265006025	Welders	G4	120	2419	208	70	16	0.51	0.55
Light-duty Commercial	2265006025	Welders	G4	175	166	208	45	16	0.51	0.7
Light-duty Commercial	2265006030	Pressure Washers	G4	50	132	115	29	13	0.85	0.7
Light-duty Industrial	2265003010	Aerial Lifts	G4	50	1044	361	33	8	0.46	0.7
Light-duty Industrial	2265003010	Aerial Lifts	G4	120	977	361	67	10	0.46	0.55
Light-duty Industrial	2265003020	Forklifts	G4	120	4834	1800	70	10	0.3	0.55
Light-duty Industrial	2265003020	Forklifts	G4	175	176	1800	146	2	0.3	0.55
Light-duty Industrial	2266003020	Forklifts	C4	120	14160	1800	70	10	0.3	0.55
Light-duty Industrial	2266003020	Forklifts	C4	175	516	1800	146	2	0.3	0.55
Total					53326					

[a] Fuel Type: C4 = LPG or CNG (4-stroke), G4 = gasoline (4-stroke)
[b] HP Class = Upper boundary of HP range
[c] Activity, hours per year
[d] BSFC, lbs/hp-hr

b. Usage

Tables 17 and 18 also present the following usage information for each type of equipment: horsepower class, average horsepower, load factor, hours of operation per year, years of equipment life, and an average BSFC. For the non-preempted subset, the 2010 California statewide inventory data were subdivided into compressed gas and gasoline equipment for each equipment type, both for population purposes and because the usage data for compressed gas and gasoline engines were quite different for some of the equipment types. The preempted subset also lists gasoline and compressed gas equipment separately, although there are only two types of equipment in the preempted subset that use compressed gas fuel: forklifts in the 120 horsepower class, and forklifts in the 175 horsepower class.

Population-weighted usage data were then calculated for each equipment type, as well as for the non-preempted (M11) and preempted (M12) equipment subsets. Results of these calculations are presented in Appendix A. Average population-weighted usage data for all equipment types by fuel used (compressed gas or gasoline), for each subset (non-preempted and preempted), are summarized in Table 19.

TABLE 19. CALIFORNIA POPULATION WEIGHTED AVERAGE USAGE DATA FOR M11 AND M12 EQUIPMENT

	Comp. Gas	Gasoline	Weighted Average
Non-Preempted			
Average hp	49.0	46.9	47.2
Use, Hours/yr	1515	310	514
Load Factor	0.34	0.64	0.59
Useful Life, years	4.4	13.8	12.2
Preempted			
Average hp	73	69	70
Use, Hours/yr	1800	427	805
Load Factor	0.30	0.53	0.46
Useful Life, years	10	13	12

Population-weighted activity data from Table 19 were used in the cost-effectiveness analysis in Section II.C.4. However, the emission inventory in Section II.C.3 was calculated from the population-weighted activity data given in Appendix A for each equipment type individually, then summed to obtain the total emission inventory.

2. Costs

This section presents the methodology and results of analysis to obtain the retail price equivalent (RPE) of the recommended emission control technologies, along with the assumptions used in the analysis. The first two sections discuss two items that are needed to perform the cost analysis: recommended emission control technology, and annual equipment sales data. Next, the cost analysis methodology and estimates of its components are discussed. Lastly, the RPE for the recommended control technology is presented.

a. Recommended Emission Control Technology

A closed-loop, electronic fuel injection system with three-way catalyst was recommended to meet the SIP HC and NO_x reduction goals. Cost-effectiveness analysis was performed based on the use of this emission control technology.

To determine estimated costs of the recommended control technology, it was necessary to identify the required added components. Major components for a closed-loop, electronic fuel injection system with three-way catalyst would include the following:

- Throttle-body fuel injector
- Fuel pump and pressure regulator
- Exhaust gas oxygen (EGO) sensor
- Electronic engine control module
- Three-way catalytic converter (TWC)

Some engines may require the use of exhaust gas recirculation (EGR) to further reduce NO_x emissions. To provide a conservative estimate, the costs for an EGR system were included in the analysis. An EGR system would include an EGR valve and a transfer tube.

b. Cost of Emission Reduction Technology

Two engines in the M11 category were found that are offered with complete feedback electronic fuel control. One system is manufactured by Bosch. Bosch stated that their EFI system for small engines could be provided to the engine manufacturer for $100 each, if total demand were 500,000 units. The second EFI fuel system plus control module is listed at $690 to distributors.

Zenith Fuel Systems supplied information on carburetor costs. Carburetor cost to an engine manufacturer can vary from $100 for a very basic carburetor to $350 for a sophisticated carburetor with an electronically controlled throttle. The Zenith open loop, throttle-body fuel injection system costs approximately $550 (with the same features as the $350 carburetor), including the electronic control module. The closed loop version would cost only about $50 more, because the hardware and software were developed to permit adding the closed-loop feature in the future. Thus, electronic control costs about $200 more than standard carburetion, and closed loop electronic control costs about $250 more.

Two types of catalysts were investigated for this project: oxidation catalysts (sometimes called two-way) and three-way catalysts. MECA reports that both two- and three-way catalyst systems are used on industrial lift trucks. These are installed in one of two configurations -- a direct in-line installation in the exhaust pipe typically close-coupled to the manifold, or as a catalytic exhaust muffler which replaces the OEM muffler and requires no modification to existing brackets.

Most of these are two-way systems which are designed to reduce CO and HC with efficiencies of more than 90 percent. The large majority of these systems are the muffler replacement type. At low sales volumes, these systems cost in the range of $400 to $600. With the wide range of truck models available, MECA estimates that the highest production of a particular converter muffler model will be on the order of 5000 units per year, even if all lift trucks sold in the U.S. were required to use converter mufflers. At these higher volumes, MECA estimates that the cost of these units would be from $150 to $200.

In the last few years, three-way catalyst systems have been introduced into the industrial truck marketplace. Like two-way systems, these can be either a direct in-line fit, or a muffler replacement. A controller is sold with the converter to control the engine near stoichiometric. Currently, the cost of three-way systems including the controller is in the range of $1000. At larger sales volumes, MECA expects the per unit cost to fall into the $500 to $600 range.

A catalyst manufacturer commented that for an off-road application, it might be cheaper to use an automotive converter because of the number of units produced, rather than a special design, even if the automotive converter was more heavily loaded with precious metals than required for the off-highway application.

With the idea that automotive converters might be less costly than special order converters, local Ford and Chevrolet dealership parts departments were called to obtain prices on converters for cars with four-cylinder engines. These single unit, retail prices are shown in Table 20.

TABLE 20. RETAIL REPLACEMENT PART PRICES FOR SEVERAL AUTOMOTIVE CONVERTERS

Model Year	Car Model and Engine	Converter Part Number	Price
1996	Ford Escort, 1.9L, four-cylinder	F6C2-5E212LA	$316
1996	Ford Contour, four-cylinder	F7F2-5E212FL	$280
1996	Chevrolet Cavalier, 2.4L, four-cylinder	25160527	$378
		Average	$325

Since there are a number of automotive derivative engines in the M11 category and these engines have been derated from their automotive applications, the automotive converters should be sufficiently sized and loaded for the off-road applications. Thus, single unit retail costs of three-way converters should be approximately $300.

c. Annual Sales Data

While there were some population estimates for this off-road equipment category, it was difficult to obtain annual sales data for category equipment. Nonetheless, EPA's Non-Road Equipment and Vehicle Emissions Study (NEVES)[(18)], and the California Off-road Mobile Source Emission Inventory Model (OFFROAD) are two major sources of information that one can use to estimate annual sales data.

Age distribution information in the OFFROAD model was used to estimate annual sales data. Information in the NEVES, statistical data on U.S. lift truck shipments provided by the Industrial Truck Association (ITA), and confidential nationwide sales data from an off-road engine manufacturer (non-lift truck industrial equipment) were used to verify sales estimates.

According to ITA data, average annual U.S. shipments of IC engine-powered industrial truck equipment (including shipments of Japanese members) from 1993 to 1997 were 60,000 units. California sales were estimated from population data. California's industrial truck population (49,000 units), comprises 13.5 percent of the national population (363,000 units). Using this value, average annual sales of industrial truck equipment in California were estimated to be about 8,000 units. Adding sales for all other equipment manufacturers, the annual sales in California for this equipment category were estimated to be 15,000 units.

Based on the OFFROAD age distribution, the percent of total equipment with less than one year in service in 2010 was about 26 percent as shown in Table 13. Accounting for overlap between zero and one year old equipment, an estimate of 20 percent new equipment was considered conservative. As shown in II.C.1, the total California population for this equipment category, including both non-preempted and preempted equipment, is about 83,000 units. Twenty percent of the population is about 16,600 units, which is comparable to the 15,000 units estimated from nationwide sales data. California populations of non-preempted and preempted equipment are about 30,000 and 53,000 units, respectively. Therefore, the average annual sales of non-preempted and preempted equipment, based on 20 percent of the respective populations, are estimated to be 6,000 units and 10,600 units. These values were used in the cost analysis.

d. Retail Price Equivalent Methodology

In order to bring some order and reproducibility to cost estimates of emission control technology, EPA has developed a standard retail price equivalent (RPE) technique.[19] EPA's RPE methods were first outlined by Lindgren [20] in a study done for EPA in 1978, and later refined by Putnam, Hayes, and Bartlett.[21] Many cost-effectiveness studies have been performed for EPA and ARB based on this RPE technique. AECI's staff has used this RPE technique in a number of recent EPA and ARB cost-effectiveness studies.[22,23,24,25]

Cost analysis includes an estimate of the incremental variable manufacturing costs (e.g., components/system and assembly labor costs), fixed costs for the emission control technology (e.g., tooling and engineering design and development costs), and the manufacturer and dealer markup. The basic equation for the RPE of a given vehicle or engine modification is given by:

$$RPE = ((SP + AL + AO) * MM + RD + TE + WC) * DM$$

where:

- RPE is the retail price equivalent;
- SP is the supplier price charged to the assembler for the components and subassemblies involved;
- AL is the direct cost of assembly labor for installing the components;
- AO is the manufacturer's assembly overhead cost per unit;
- MM is the manufacturer's markup percentage, to account for corporate overhead and profit;
- RD is the manufacturer's research and development cost per unit;
- TE is the manufacturer's tooling cost per unit;
- WC is the manufacturer's added warranty cost, per unit; and
- DM is the dealer's markup percentage.

e. Elements of the RPE Equation

To obtain the information needed to calculate the RPE, solicitations were made to members of the Technical Advisory Committee (TAC), and engine manufacturers and suppliers, to provide data and cost information on potential control technology. AECI staff also obtained some retail prices on emission control components from local automobile and equipment distributors, and aftermarket parts suppliers. Typical manufacturer and dealer markup percentages were also obtained from industrial engine and equipment manufacturers and dealers via AECI solicitations. Individual elements of the RPE equation are discussed in the paragraphs below.

(1) Dealer and Manufacturer Markups (DM and MM)

In order to determine typical dealer markup percentages, several local industrial equipment dealers (Caterpillar, Ford, Mitsubishi, Nissan, and Toyota) were contacted. All of the dealers claimed that it is a very competitive market.[26] Three dealers indicated that the typical dealer markup was 5 to 10 percent, and one dealer estimated 8 to 15 percent. While the range was considered low for such a small niche market (average dealer markup for lawn and garden equipment was determined to be about 23 percent[22]), the high turnover rate of dealerships may well confirm that the 5 to 10 percent range is legitimate. A conservative 10 percent dealer markup was used in the cost analysis. Based on conversation with these dealers, the parts markup is substantially higher at an average of 30 percent.

For the manufacturer markup percentage, only one manufacturer, was willing to provide estimates for typical manufacturer markup percentages on industrial engines. They indicated that, while markups for manufacturers vary, typical manufacturer markups were in the 20 to 30 percent range, and the markup for parts was about 50 percent. While this range is slightly higher than those for lawn and garden equipment manufacturers (5 to 10%), and automotive engine manufacturers (10 to 20%), the markup percentages seem reasonable. An average value of 25 percent manufacturer markup was used in the cost analysis.

(2) Variable Costs (SP, AL, and AO)

Cost analysis includes an estimate of incremental variable costs due to use of emission control technology. Incremental variable costs include added hardware and manufacturing labor costs.

Cost data collected indicated that a closed-loop, throttle body fuel injection system would cost about $200 to $600 to retailers. Using a 50 percent parts markup, the cost to manufacturers would be about $130 to $400. Cost of a complete EGR system was $75 to retailers, or about $50 to manufacturers. For a three-way catalyst, cost to retailers ranged from $200 to $400, which means $130 to $270 to manufacturers.

To determine costs to the manufacturer of emission control components, a top-down-approach was used on retail price information on 1.9L and 3.0L engine parts, with dealer and manufacturer markups removed. While retail prices for emission control components were rarely available, some cost estimates to the retailers were available. Additional information was gathered from local automobile and equipment distributors (Ford, Mitsubishi, and Nissan), and aftermarket parts suppliers (Chief, Kragen, and NAPA).[27] Based on this information, a closed-loop, throttle body fuel injector costs about $80 to $120, a fuel pump and regulator cost about $80 to $100, an EGO sensor costs about $65 to $75, an ECM costs about $180 to $220, an EGR assembly costs about $70 to $80, and a three-way catalytic converter costs about $140 to $160.

Using average values for these components, discounted for a 30 percent dealer markup and a 50 percent manufacturer markup, the costs to manufacturers for these components are summarized in Table 21. As this table shows, the estimated cost for a closed-loop, throttle body fuel injection system is $236. A three-way catalyst assembly costs about $77, and an EGR assembly costs about $39.

TABLE 21. MANUFACTURER COMPONENT COST ESTIMATES BASED ON RETAIL PRICE INFORMATION

Hardware	Cost to Manufacturer
Throttle body fuel injector	$46
Fuel pump and regulator	51
EGO	36
ECM	103
EGR assembly	39
Catalytic converter assembly	77

For the cost analysis, incremental costs of $300, $75, and $40 were used for the complete closed-loop fuel injection system, three-way catalyst, and EGR assemblies, respectively. The cost estimate for the fuel injection system includes costs for other peripheral components such as the magnetic pickup, crankshaft gear, and electronic ignition coil for gasoline engines, and the intake MAP sensors for LPG engines. By using the fuel-injection system, manufacturers would save the cost of the carburetor, which is estimated to be $50.

Adding new components to an engine requires additional manufacturing and assembly labor. It was estimated that it would add about half an hour to produce and assemble the new parts. Assuming a general labor rate of $40 per hour with a 40 percent overhead rate, the added manufacturing and assembly labor cost is about $28. Incremental variable costs are summarized in Table 22.

TABLE 22. VARIABLE COSTS TO MANUFACTURER

Incremental Variable Cost Component	Costs
Hardware Costs	
Complete throttle body fuel injection system	$300
Catalytic converter assembly	75
EGR assembly	40
Elimination of carburetor	-50
Manufacturing and Assembling Labor	
Labor	0.5 hr
Cost @ $40/hr	$20
Assembly overhead @40%	$8
Total variable costs to manufacturer	$393

(3) Fixed Costs (RD, TE, and WC)

Since the recommended emission control technology has been used in the automotive industry and on some industrial equipment for years, minimum or no research and development effort is required. However, engineering and development will be required to redesign the engine and the equipment to accommodate the emission control package.

Based on the information compiled, there are about 16 manufacturers that produce engines used in the M11/M12 equipment category, and eight are considered major manufacturers. In the cost analysis, it was estimated that the necessary changes in engine and equipment design would require the effort of two engineers from each of the eight major manufacturers for about two years. Smaller manufacturers would be more likely to depend on their suppliers, and would assign only a few of their own staff to this effort. To account for this, another 10 staff are assumed to be employed by the minor manufacturers and technology suppliers. Thus, the total engineering design and development (D&D) effort would amount to about 26 engineer-years per year. For typical engineering salaries and overhead rates, the cost of an engineer working full-time for a year (including salary, benefits, physical and administrative overhead, and other costs) is estimated to be about $100,000. With this loaded engineer cost, the total cost of D&D staff time alone for designing emission-controlled off-road engines would be about $5.2 million for the two year period, or $2.6 million per year.

Changes in engine hardware would require corresponding changes in a company's technical support services--service manual, technical training, etc. Based on information gathered for previous studies, an estimate of $13 per engine was believed to be reasonable for technical support costs on this equipment.

Costs of test engines, emission testing, special materials, travel, and other similar expenses will add substantially to the D&D costs. For instance, it is estimated that development efforts will require about 300 emission tests per year per manufacturer, which is about six tests per week per manufacturer. With eight major manufacturers, the total would amount to 2,400 tests per year. Assuming another 300 emission tests that would be performed by minor manufacturers and suppliers, the total emission tests would be 2,700. Using an estimate of $1,000 per test, emission tests would cost about $2,700,000. Assuming test engines, travel, other D&D, and test materials, etc., would cost about $1 million, total D&D costs would likely be about $6.4 million per year.

Since adapting existing technology to off-road engines does not require substantial lead time, it was estimated that it would take the industry about two years to fully integrate the technology into production. Thus, the total cost of the D&D effort should be about two years at $6.4 million per year, or $12.8 million. With interest at 10 percent per year, and amortizing the costs over 10 years, the amortized D&D costs for developing emission-controlled off-road engines would be about $2.1 million per year. Using the annual sales data presented earlier, the D&D cost per engine for non-preempted equipment with an average annual sales of 6,000 units is about $346. If regulations were to apply to both preempted and non-preempted equipment (total annual California sales of 16,000), the cost per unit would be $130.

Designing, developing, and producing new engines would also require tooling costs. Since almost all major engine manufacturers include some form of tooling costs in the development of new products, it was estimated that each major manufacturer would spend about half a million dollars on tooling costs in order to produce emission-controlled engines. This would amount to about $4 million for eight manufacturers. Amortizing the $4 million tooling costs at 10 percent interest over ten years yields a per engine cost of about $108 for non-preempted equipment, and $41 for all (preempted and non-preempted) equipment.

Assuming the emission-controlled engines will need to maintain their emission levels throughout their lifetime, an added warranty cost for the added components would be incurred by the manufacturer. In an ARB mail-out [(28)], ARB estimated the warranty cost for new emission control components that were used in low-emission vehicles. ARB estimated that the failure rate for these components was about 0.1 percent. Since the proposed emission control technology used in the off-road equipment is a developed technology, the failure rate should be of the same order of magnitude. A conservative estimate of 0.5 percent failure rate was used in this study to account for failures due to the introduction of technology new to this industry. Costs that contribute to total fixed costs are tabulated in Table 23.

f. Retail Price Equivalent

Table 24 presents the incremental retail price equivalents for non-preempted equipment, and all equipment (preempted + non-preempted). As this table shows, the RPE for the non-preempted equipment is $1,043, and the RPE for all equipment is $731.

3. Emissions

The equipment in this category is diverse in type and use. In order to estimate the emissions from an "average engine" it is necessary to calculated the total emission inventory based on the baseline engine emissions, and for each equipment type, the average engine rated power, load factor, and hours per year of usage. Once the total emission inventory is known, it can be multiplied by the average life, and then divided by the population to obtain per engine lifetime emissions.

a. Engine Emission Factors

Baseline exhaust emissions and BSFC data for this equipment category are presented in Table 25. These average emissions values were taken from Section II-B. Average emission values for gasoline and LPG were used in the calculation of emission inventory, and in the cost-effectiveness analysis. While the engines tested to obtain the baseline emission data were specifically chosen from the non-preempted (M11) subset, for this cost-effectiveness analysis, these emissions were used for the preempted (M12) subset as well.

TABLE 23. FIXED COSTS TO MANUFACTURER

Cost Component	Non-Preempted	All Equipment
Engineering Labor Costs		
Number of firms (major)	8	
Engineering staff/firm	2	
Total staff	16	
Staff other small firms	10	
Total staff	26	
Loaded salary/year	$100,000	
Total engineering labor/year	$2,600,000	
Technical Support Costs		
Training, tech. pubs.	$80,000	
Testing Costs		
No. of tests/year/firm	300	
Number of tests/year	2400	
Other tests/year	300	
Total tests/year	2700	
Cost/test	$1,000	
Total test cost/year	$2,700,000	
Total of above costs	$5,380,000	
Other engineering costs	$1,000,000	
Grand total	$6,380,000	
Number of year effort	2	
Total D&D costs	$12,760,000	
Amortized over 10 years, per year	$2,076,631	
Number of Equipment	6,000	16,000
D&D Costs, $/unit	**$346**	**$130**
Tooling Costs		
Tooling cost/firm	$500,000	
Total, 8 firms	$4,000,000	
Amortized over 10 years, per year	$650,982	
Tooling Costs, $/unit	**$108**	**$41**

TABLE 24. RETAIL PRICE EQUIVALENT FOR NON-PREEMPTED AND ALL EQUIPMENT

Cost Component	Non-Preempted	All Equipment
Incremental Hardware Costs		
Complete closed-loop FI system	$300	
Catalytic converter assembly	75	
EGR assembly	40	
Elimination of carburetor	-50	
Assembly labor (hours)	0.5	
Cost @ $40/hr	20	
Assembly overhead @ 40%	8	
Variable cost to manufacturer	$394	
Mfr's markup @ 25%	98	
Engr. design & dev. costs	$346	$130
Tooling costs	108	41
Warranty costs	2	2
Total cost to dealer	948	665
Dealer's markup @ 10%	95	66
RPE	$1,043	$731

TABLE 25. SUMMARY OF BASELINE EMISSIONS OF M11 EQUIPMENT

Engine	Cycle	Fuel	Emissions (g/hp-hr) HC	CO	NO_x	BSFC (lb/hp-hr)	Remarks
F	C2	Gasoline	3.23	49.9	13.7		Average of 3 different carburetors
A	C2	Gasoline	1.69	20.1	12	0.554	Current project
B	C2	Gasoline	1.49	16.3	8.32	0.579	Current project
C	C2	Gasoline	3.81	50.7	7.74	0.616	Current project
D	C2	Gasoline	3.99	124	5.38	0.671	Current project
E	C2	Gasoline	18.7	684	1.06	1.43	Current project
40 HP Lift Truck	C2	LPG	1.17	5.74	13.8		Average of two tests (ARB contract A198-076)
F	C2	LPG	2.9	141	4.93		One test
G	C2	LPG	2.28	27.3	15.4		Two tests. Fuel system"x"
G	C2	LPG	1.88	5.32	16.73		Two tests. Fuel system"y"
B	C2	LPG	0.94	7.37	11.7	0.526	Current project
C	C2	LPG	1.7	8.8	11.5	0.54	Current project
E	D2	Gasoline	10.65	479	1.7	1.1	Current project
D	D2	LPG	0.89	2.08	9.86	0.455	Current project
Average LPG	all	LPG	1.68	28.23	11.99	0.507	
Average Gasoline	all	Gasoline	6.22	203.4	7.13	0.825	

To obtain the engine emission factors from controlled equipment, it was necessary to estimate the per engine emission reductions for controlled engines. The ARB staff requested that the emission control level be based on technologically feasible reductions. From the technologically feasible reductions presented in Section II.B.3., the reductions used in this analysis were: a 90 percent reduction in baseline HC emissions, a 95 percent reduction in baseline CO emissions, and a 77 percent reduction in baseline NO_x emissions. These reductions will be referred to as the 90/95/77 control strategy. Using these percentage reductions, and the average LPG and gasoline baseline emissions from Table 25, a set of emission factors was developed for both controlled LPG and gasoline engines. These calculated emission factors are presented in Table 26.

TABLE 26. CALCULATED EMISSION FACTORS FOR CONTROLLED GASOLINE AND LPG ENGINES

	Emission Factor, g/hp-hr			
	HC	CO	NO_x	HC + NO_x
Gasoline-fueled	0.62	10.17	1.64	2.26
LPG-fueled	0.17	1.41	2.76	2.93

b. Total Reductions in 2010 Daily Emissions

Using the 2010 population and usage data, and the average baseline engine exhaust emission data from Table 25, the uncontrolled mass emissions per day were calculated for the population of each type of equipment in the M11 and M12 subsets. The mass emissions per day for controlled equipment was similarly calculated, but using the calculated controlled emission factors in Table 26. The daily emissions for each individual equipment type were summed to obtain the total daily emission inventory for each subset (M11 and M12). See Appendix A for these calculations.

The total daily emission inventory for the uncontrolled and controlled engines, together with the differences in uncontrolled and controlled emissions for the M11 and M12 subsets, are listed in Table 27. The difference in the uncontrolled and controlled emission inventory represents the total reduction that would be obtained if 100 percent of the equipment in-use was emission controlled in 2010. In other words, this is the maximum reduction that would be obtained with the 90/95/77 control strategy. While the effective date of emission regulations is undefined at this time, it is unlikely that 100 percent of the equipment in-service would have emission controls in 2010. Table 28 lists the emissions reductions that would be obtained with various percentages of emission controlled equipment in-service in 2010.

TABLE 27. DAILY EMISSION INVENTORY FOR UNCONTROLLED AND CONTROLLED EQUIPMENT IN M11 AND M12 CATEGORIES

	Daily Emissions Inventory, tons per day			
	HC	CO	NO_x	HC + NO_x
Non-Preempted (M11)				
Uncontrolled	4.50	139.1	8.19	12.69
100 % Controlled	0.45	7.0	1.88	2.33
Reduction	4.05	132.1	6.31	10.36
Preempted (M12)				
Uncontrolled	11.77	338.3	30.99	42.76
100% Controlled	1.18	16.9	7.13	8.30
Reduction	10.59	321.4	23.86	34.46

TABLE 28. EMISSION INVENTORY REDUCTIONS IN 2010 WITH VARIOUS PERCENTAGES OF CONTROLLED EQUIPMENT IN SERVICE

Percent of controlled in-service equipment	Reduction in Inventory, tons per day			
	HC	CO	NO_x	HC + NO_x
Non-preempted (M11)				
20%	0.81	26.4	1.26	2.07
40%	1.62	52.8	2.52	4.14
60%	2.43	79.3	3.79	6.22
80%	3.24	105.7	5.05	8.29
100%	4.05	132.1	6.31	10.36
Preempted (M12)				
20%	2.12	64.3	4.77	6.89
40%	4.24	128.6	9.54	13.78
60%	6.35	192.8	14.32	20.67
80%	8.47	257.1	19.09	27.56
100%	10.59	321.4	23.86	34.45

c. Average Per Engine Lifetime Emissions

Average engine lifetime emissions are required to calculate the cost-effectiveness of the proposed emission controls. Total lifetime uncontrolled mass emissions were calculated for the population of each type of equipment in the M11 and M12 subsets by multiplying the daily emissions in Table 27 by the life of each equipment type. Lifetime emissions for controlled equipment were similarly calculated. Individual equipment type lifetime emissions were then summed and divided by the total population to provide average per engine lifetime emissions for uncontrolled and controlled engines. Since the cost of emission control equipment can be different for LPG and gasoline fuel engines, lifetime emissions were calculated separately for LPG and gasoline fueled equipment. See Appendix A for these calculations.

Average engine lifetime mass emissions for the uncontrolled and controlled engines, together with the differences in the uncontrolled and controlled emissions, are listed in Table 29. The difference in the uncontrolled and controlled emissions is the average lifetime emission reduction per engine. It is this value that will be used to calculate the dollars per pound of emissions reduction in the cost-effectiveness analysis.

TABLE 29. AVERAGE PER ENGINE LIFETIME EMISSIONS FOR M11 AND M12 EQUIPMENT

	Compressed Gas (LPG & CNG), Lifetime Emissions/Engine, lb				Gasoline, Lifetime Emissions/Engine, lb			
	HC	CO	NO_x	HC + NO_x	HC	CO	NO_x	HC + NO_x
All Non-preempted Equipment								
Uncontrolled	276	4644	1972	2249	1099	35939	1259	2359
Controlled	28	232	454	481	110	1797	290	400
Reduction	249	4412	1519	1767	989	34142	970	1959
Preempted Agricultural Equipment								
Uncontrolled	0	0	0	0	1130	36942	1295	2425
Controlled	0	0	0	0	113	1847	298	411
Reduction	0	0	0	0	1017	35095	997	2014
Preempted Construction Equipment								
Uncontrolled	1413	23736	10080	11493	2433	79520	2787	5219
Controlled	141	1187	2318	2460	243	3976	641	884
Reduction	1271	22549	7762	9033	2189	75544	2146	4335
ALL Preempted Equipment								
Uncontrolled	1413	23736	10080	11493	1902	62180	2179	4081
Controlled	141	1187	2318	2460	190	3109	501	691
Reduction	1271	22549	7762	9033	1712	59071	1678	3390

d. Total Emission Reductions

Total emission reductions were determined for two different definitions of "total." The first total emission reductions were the reductions in daily emission inventory (expressed in tons per day) for all the equipment, and various subsets of the equipment. These emission reductions are summarized in Table 30 in tons per day, and as a percentage of the total uncontrolled daily emission inventory.

TABLE 30. INVENTORY AND PERCENTAGE EMISSION REDUCTIONS IN 2010 WITH VARIOUS PERCENTAGES OF CONTROLLED EQUIPMENT IN-SERVICE

Percent of Controlled Equipment in Service	Reduction in Inventory, tons per day				Reduction, Percent of Uncontrolled			
	HC	CO	NO_x	$HC + NO_x$	HC	CO	NO_x	$HC + NO_x$
Non-preempted (M11)								
20%	0.81	26.4	1.26	2.07	18.0	19.0	15.4	16.3
40%	1.62	52.8	2.52	4.14	36.0	38.0	30.8	32.7
60%	2.43	79.3	3.79	6.22	54.0	57.0	46.2	49.0
80%	3.24	105.7	5.05	8.29	72.0	76.0	61.6	65.3
100%	4.05	132.1	6.31	10.36	90.0	95.0	77.0	81.6
Preempted (M12)								
20%	2.12	64.3	4.77	6.89	18.0	19.0	15.4	16.1
40%	4.24	128.6	9.54	13.78	36.0	38.0	30.8	32.2
60%	6.35	192.8	14.32	20.67	54.0	57.0	46.2	48.3
80%	8.47	257.1	19.09	27.56	72.0	76.0	61.6	64.5
100%	10.59	321.4	23.86	34.45	90.0	95.0	77.0	80.6

The second total emission reduction calculated was the average individual engine lifetime emission reduction for engines in the various subsets, expressed in pounds. These emission reductions are summarized in Table 31 for LPG and gasoline engines for the M11 subset, and the agricultural, construction and total components of the M12 subset.

TABLE 31. AVERAGE PER ENGINE LIFETIME EMISSION REDUCTIONS FOR M11 AND M12 EQUIPMENT

	Average LPG Lifetime Emissions, pounds per engine				Average Gasoline Lifetime Emissions, pounds per engine			
	HC	CO	NO_x	$HC + NO_x$	HC	CO	NO_x	$HC + NO_x$
M11	249	4412	1519	1767	989	34142	970	1959
M12 Agricultural	[redacted]				1017	35095	997	2014
M12 Construction	1271	22549	7762	9033	2189	75544	2146	4335
M12 Total	1271	22549	7762	9033	1712	59071	1678	3390

4. Cost-effectiveness

Cost-effectiveness analysis was performed based on the incremental retail price equivalent (RPE) and the emission reduction realized by the emission control technology. Cost-effectiveness was calculated for both non-preempted and all equipment. Within the preempted equipment, cost-effectiveness results were also calculated for agricultural and construction equipment. Since the LPG and gasoline equipment has significant differences in emission levels and activity data, separate cost-effectiveness results were calculated for LPG and gasoline equipment.

a. Cost-Effectiveness for Non-Preempted Equipment (M11)

Usage data for different equipment categories and fuel types were presented in Section II.C.1. Lifetime emission reductions per engine, based on emission factor reductions of 90 percent for HC, 95 percent for CO, and 77 percent for $NO_{x,}$ were presented in Section II.C.3. RPEs were presented in Section II.C.2.

Using these data, cost-effectiveness values were calculated. For non-preempted gasoline and LPG equipment, cost-effectiveness with all costs allocated to each emission (HC, CO, NO_x), as well as allocated to HC+NO_x emissions, are shown Table 32. Cost-effectiveness ranged from \$0.66 to \$2.81 per pound of HC emissions, \$0.46 to \$0.67 per pound of NO_x emissions, \$0.34 to \$0.39 per pound of HC+NO_x emissions, and \$0.02 to \$0.16 per pound of CO emissions.

b. Cost-Effectiveness for All Equipment (M11 & M12)

Cost-effectiveness results for all gasoline and LPG equipment are shown in Table 33. Cost-effectiveness ranged from \$0.35 to \$0.73 per pound of HC emissions, \$0.13 to \$0.35 per pound of NO_x emissions, \$0.10 per pound of HC+NO_x emissions, and \$0.01 to \$0.04 per pound of CO emissions.

For the preempted equipment, cost-effectiveness results were also calculated for agricultural and construction equipment separately, as shown in Table 34. Cost-effectiveness results for agricultural gasoline equipment was \$0.82, \$0.82, \$0.40 and \$0.02 per pound of HC, NO_x, HC+NO_x, and CO emissions, respectively. Since there was no equipment in the LPG category, no cost-effectiveness results for agricultural LPG equipment were calculated.

As shown in Table 34, the cost-effectiveness results for construction equipment were quite similar to those for all equipment. Cost-effectiveness ranged from \$0.25 to \$0.57, \$0.10 to \$0.27, \$0.08 to \$0.13 and \$0.01 to \$0.03 per pound for HC, NO_x, HC+NO_x and CO emissions, respectively.

TABLE 32. COST-EFFECTIVENESS RESULTS FOR NON-PREEMPTED EQUIPMENT

Cost-Effectiveness Analysis: Non-preempted 25-175 hp Offroad Gasoline and LPG (Industrial) Equipment				
			Gasoline	LPG
Average Lifespan (yr)			14	4.4
Average Usage (hr/yr)			310	1515
Average Horsepower			47	49
Average Load Factor			0.64	0.34
Emission Reductions				
	Emissions			
	HC	**NOx**	**HC+NO$_x$**	**CO**
Average LPG Engine (g/bhp-hr)	1.68	11.99	13.67	28.23
Controlled Engine (g/bhp-hr)	0.17	2.76	2.93	1.41
Emission Reduction (g/bhp-hr)	1.51	9.23	10.74	26.82
Emission Reduction (lb/unit)	370	2261	2631	6567
Average Gasoline Engine (g/bhp-hr)	6.22	7.13	13.35	203.43
Controlled Engine (g/bhp-hr)	0.62	1.64	2.26	10.17
Emission Reduction (g/bhp-hr)	5.60	5.49	11.09	193.26
Emission Reduction (lb/unit)	1588	1557	3145	54810
Incremental RPE				
Incremental RPE			$1,043	$1,043
Cost-Effectiveness for Incremental RPE ($/lb)				
All Costs Allocated to HC Emissions			**0.66**	**2.81**
All Costs Allocated to NOx Emissions			**0.67**	**0.46**
All Costs Allocated to HC+ NOx Emissions			**0.34**	**0.39**
All Costs Allocated to CO Emissions			**0.02**	**0.16**

TABLE 33. COST-EFFECTIVENESS RESULTS FOR ALL (M11 & M12) EQUIPMENT

Cost-Effectiveness Analysis: All 25-175 hp Offroad Gasoline and LPG Equipment				
			Gasoline	**LPG**
Average Lifespan (yr)			13.1	8.4
Average Usage (hr/yr)			382	1,729
Average Horsepower			60	67
Average Load Factor			0.57	0.31
Emission Reductions				
	Emissions			
	HC	**NO_x**	**$HC+NO_x$**	**CO**
Average LPG Engine (g/bhp-hr)	1.68	11.99	13.67	28.23
Controlled Engine (g/bhp-hr)	0.17	2.76	2.93	1.41
Emission Reduction (g/bhp-hr)	1.51	9.23	10.74	26.82
Emission Reduction (lb/unit)	998	6,092	7,090	17,697
Average Gasoline Engine (g/bhp-hr)	6.22	7.13	13.35	203.43
Controlled Engine (g/bhp-hr)	0.62	1.64	2.26	10.17
Emission Reduction (g/bhp-hr)	5.60	5.49	11.09	193.26
Emission Reduction (lb/unit)	2,119	2,078	7,317	73,147
Incremental RPE				
Incremental RPE			$731	$731
Cost-Effectiveness for Incremental RPE ($/lb)				
All Costs Allocated to HC Emissions			**0.35**	**0.73**
All Costs Allocated to NO_x Emissions			**0.35**	**0.13**
All Costs Allocated to HC+ NO_x Emissions			**0.10**	**0.10**
All Costs Allocated to CO Emissions			**<0.01**	**0.04**

TABLE 34. COST-EFFECTIVENESS RESULTS FOR PREEMPTED AGRICULTURAL AND CONSTRUCTION EQUIPMENT

Cost-Effectiveness Results for Preempted Agricultural and Construction Equipment				
	Agricultural		Construction	
	Gasoline	LPG	Gasoline	LPG
Average Lifespan (yr)	15	n/a	11	10
Average Usage (hr/yr)	118	n/a	639	1800
Average Horsepower	79	n/a	62	73
Average Load Factor	0.54	n/a	0.51	0.30
Emission Reductions				
	Emissions			
	HC	NO_x	HC+NO_x	CO
Average LPG Engine (g/bhp-hr)	1.68	11.99	13.67	28.23
Controlled Engine (g/bhp-hr)	0.17	2.76	2.93	1.41
Emission Reduction (g/bhp-hr)	1.51	9.23	10.74	26.82
Emission Reduction, Construction (lb/unit)	1269	7746	9015	22502
Average Gasoline Engine (g/bhp-hr)	6.22	7.13	13.35	203.43
Controlled Engine (g/bhp-hr)	0.62	1.64	2.26	10.17
Emission Reduction (g/bhp-hr)	5.60	5.49	11.09	193.26
Emission Reduction, Agricultural (lb/unit)	891	900	1818	31681
Emission Reduction, Construction (lb/unit)	2857	2745	5543	96611
Incremental Cost	$731	n/a	$731	$731
Cost-Effectiveness for Incremental RPE ($/lb)				
All Costs Allocated to HC Emissions	**0.82**	**n/a**	**0.25**	**0.57**
All Costs Allocated to NO_x Emissions	**0.82**	**n/a**	**0.27**	**0.10**
All Costs Allocated to HC+ NO_x Emissions	**0.40**	**n/a**	**0.13**	**0.08**
All Costs Allocated to CO Emissions	**0.02**	**n/a**	**0.01**	**0.03**

c. Cost-Effectiveness

Cost-effectiveness results for non-preempted and all (non-preempted & preempted) equipment, separated by industrial, agricultural and construction categories, are summarized in Table 35. Cost-effectiveness based on HC + NO_x emission reductions ranges from \$0.08 per pound (for preempted LPG construction equipment) to \$0.40 per pound (for preempted gasoline agricultural equipment). The higher per pound cost is \$2.81 for non-preempted LPG equipment with all costs assigned to HC only.

Electronic fuel injection or improved carburetors installed on off-road equipment could provide an additional benefit of decreased fuel consumption. Nevertheless, the amount of savings from reduced fuel consumption would depend on the individual system and the extent of utilization. Using baseline fuel consumption data presented earlier in the report over the lifetime of the equipment, a 3 percent fuel consumption improvement would outweigh the incremental RPEs for all categories, assuming LPG and gasoline fuel prices of \$1.10 and \$1.30 per gallon of fuel, respectively.

TABLE 35. SUMMARY OF COST-EFFECTIVENESS RESULTS

Status	Emissions	Dollars/lb in Category			
		Agricultural	Construction	Industrial	All
Gasoline Equipment					
Preempted	HC	0.82	0.25	n/a	n/a
	NO_x	0.82	0.27		
	$HC+NO_x$	0.40	0.13		
	CO	0.02	0.01		
Non-Preempted	HC	n/a	n/a	0.66	n/a
	NO_x			0.67	
	$HC+NO_x$			0.34	
	CO			0.02	
Preempted and Non-Preempted	HC	n/a	n/a	n/a	0.35
	NO_x				0.35
	$HC+NO_x$				0.10
	CO				<0.01
LPG Equipment					
Preempted	HC	n/a	0.57	n/a	n/a
	NO_x		0.10		
	$HC+NO_x$		0.08		
	CO		0.03		
Non-Preempted	HC	n/a	n/a	2.81	n/a
	NO_x			0.46	
	$HC+NO_x$			0.39	
	CO			0.16	
Preempted and Non-Preempted	HC	n/a	n/a	n/a	0.73
	NO_x				0.13
	$HC+NO_x$				0.10
	CO				0.04

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III. PHASE II - DEMONSTRATION OF EMISSION-CONTROLLED GASOLINE/LPG ENGINES

A. Task 2.1 - Baseline Testing

1. Engines Tested

Five engines were selected by CARB for use in this program. Engines were loaned for program use by the manufacturers, provided results were coded to maintain manufacturer confidentiality. Engines were baseline tested using the recommended test procedures, and then emission reduction technologies were applied to the two engines selected for durability testing.

2. Test Equipment, Procedures, and Fuels

Emission testing was performed in Department of Emissions Research Test Cell 2, which is equipped with a 260 hp General Electric DC dynamometer. Engine load is measured with a Lebow (rotary transformer) in-line torquemeter, and engine speed is measured using a magnetic pickup with a 60-tooth gear. A full dilution CVS-PDP method complying with EPA Part 86 requirements was used for emissions sampling, analysis, and calculation. Exhaust was sampled from a primary dilution tunnel with a nominal flow rate of 1500 cfm. Dilute exhaust samples were collected in Tedlar bags and analyzed. CO and CO_2 concentrations were measured with separate non-dispersive infrared analyzers. NO_x was measured with a chemiluminescent analyzer, and HC emissions were determined with a flame ionization detector.

a. ISO 8178 Steady-State Emissions Tests

All five engines are used in variable speed applications and were tested with the ISO 8178-C2 cycle. Engines D and E were also tested using the ISO 8178-D2 cycle. Test cycle modes and weighting factors are shown in Tables 36 and 37. All engines except engine A were baseline tested with both gasoline and LPG.

TABLE 36. ISO 8178-C2 TEST MODES AND WEIGHTING FACTORS

Mode	1	2	3	4	5	6	7
Speed	Rated	Intermediate					Low Idle
% Torque	25	100	75	50	25	10	0
Weighting Factor	0.06	0.02	0.05	0.32	0.30	0.10	0.15

TABLE 37. ISO 8178-D2 TEST MODES AND WEIGHTING FACTORS

Mode	1	2	3	4	5
Speed	Rated				
% Torque	100	75	50	25	10
Weighting Factor	0.05	0.25	0.30	0.30	0.10

b. Cold- and Hot-Start Emissions Tests

To assist in definition of a simple laboratory cold-start emission test procedure, representatives of four engine and equipment manufacturers were contacted regarding typical equipment starting practices. The consensus was that driven equipment was operated in a fashion comparable to on-road vehicles. That is, as soon as the vehicle could be driven without stalling, it was driven. Two manufacturers expressed the opinion that non-mobile equipment may be given slightly more time to warm up than driven equipment. In either case, soon after start-up, this equipment produces work. Since it is good practice to not highly load a cold engine, operator's manuals warn against doing so. It was recommended to start each engine on the choke, and allow it to warm up for a short time, and then to step through the ISO test cycle in reverse order, starting with the lowest speed and load mode, and ending at the high speed and load mode.

This procedure would be hard to follow consistently without computer control of engine speed and load, and development of such control algorithms was beyond the scope of this project. However, in discussions with other TAC members, a consensus was reached that a simpler cycle would suffice, and it is outlined in Table 38. Each engine was started on the choke and idled for 30 seconds. The choke was then removed and the engine was allowed to idle for a further 30 seconds. Afterwards, the engine was operated at 10 percent load at intermediate speed for two minutes, followed by operation at 25 percent load for a further two minutes. Emissions were collected from engine start for a total of five minutes. After a 10 minute cool-down period, the hot-start test was performed, without using the choke.

TABLE 38. PROCEDURE FOR ENGINE START TESTS

Time After Engine Start	Speed	% Load	Comments
0 - 30 seconds	Idle	0	Engine is started with choke if cold-start
30 - 60 seconds	Idle	0	Choke is disengaged at 30 seconds
1 - 3 minutes	Intermediate	10	
3 - 5 minutes	Intermediate	25	

Unlike steady-state tests where diluted exhaust is collected in Tedlar bags and analyzed at a remote instrument bench, real-time emissions analysis and calculation was required for the engine start tests. For this purpose, a mobile emissions analysis instrument cart was coupled with a LabVIEW data acquisition system to enable continuous analysis of dilute exhaust and calculation of emission rates.

It should be kept in mind that this is a *research* procedure, developed for collection of preliminary cold- and hot-start emissions data. It is not a fully developed engine start procedure. Collection and analysis of real in-use engine start data would be required to develop a representative cold/hot start emission test procedure for this category.

c. Fuels

Gasoline used for testing met the specifications for California Phase II fuel. An analysis of the batch used is shown in Table 39. LPG used met commercial HD5 specifications, as shown in Table 40.

TABLE 39. CALIFORNIA PHASE II GASOLINE ANALYSIS

SUPPLIER PHILLIPS 66

LOT NO. D-018A SwRI CODE EM-2491-F

Item	CCR Specification		Supplier Analysis	SwRI Analysis
	ASTM	Unleaded		
Octane, research	D2699		97.1	97.3
Octane, motor	D2700		87.5	88
Antiknock Index		91 (min.)	92.3	92.7
Sensitivity		7.5 (min.)	9.6	9.3
Pb (organic), gm/U.S., gal	D3237	0.050 (max.)	NR	<0.001
Distillation Range:				
IBP°F	D86		102	107
10% Point, °F	D86	130-150	141	143
50% Point, °F	D86	200-210	206	205
90% Point, °F	D86	290-300	299	297
EP, °F	D86	390 (max.)	373	366
Sulfur, ppm	D1266	30-40	36	30
Phosphorus, gm/U.S.,gal	D3231	0.005	NR	<0.001
RVP, psi	D323	6.7-7.0	6.85	7.02
MTBE, vol%		10.8-11.2	11.13	11.05
Hydrocarbon Composition:				
Aromatics, %	D1319	35 (max.)	23.9	23.6
Olefins, %	D1319	10 (max.)	4.8	3.9
Saturates, %	D1319	remainder	71.3	72.5
NR - not reported				

TABLE 40. LPG FUEL ANALYSIS

Fuel Component	HD-5 Specification	Fuel Analysis
Ethane	NA	5.05%
Propylene	5.0 % vol. maximum	0.0%
Propane	90.0% vol. minimum	93.45%
Butanes and heavier	2.5% vol. maximum	1.5%

3. Steady-State Test Results

a. Engine A

During the ISO 8178-C2 cycle, the engine is operated predominately at its intermediate speed, which is required to fall between 60 percent and 75 percent of rated speed. Based on consideration given to setting the lower limit of intermediate speed to 50 percent of rated speed, a third steady-state emissions test was conducted on engine A to examine the effects of using a lower intermediate speed on C2 cycle emissions.

Table 41 summarizes the results from the steady-state emissions tests on engine A. The first two tests were conducted using the manufacturer specified intermediate speed of 1800 rpm, and the third test used an intermediate speed of 1500 rpm (50 percent of rated speed). Work-specific emissions from this third test were similar to those from the first two baseline tests. Using the lower intermediate speed, HC emissions were approximately 20 percent higher, and emissions of CO increased slightly, but there were no significant changes in NO_x emissions or fuel consumption.

TABLE 41. ENGINE A EMISSION RESULTS, ISO 8178-C2 CYCLE, GASOLINE FUEL

Test	Intermediate Speed (rpm)	Emissions (g/hp-hr)			BSFC (lb/hp-hr)
		HC	NO_x	CO	
Baseline 1	1800	1.61	11.47	19.71	0.552
Baseline 2	1800	1.77	12.45	20.47	0.555
Mean with 1800 rpm int. speed		1.69	11.96	20.09	0.554
Baseline 3	1500	2.00	12.06	20.84	0.556

b. Engine B

Emission results from engine B were lower than those from engine A. As shown in Table 42, engine B generated approximately 10 percent lower brake specific HC, 30 percent lower NO_x, and 20 percent lower CO than engine A.

TABLE 42. ENGINE B EMISSION RESULTS, ISO 8178-C2 CYCLE, GASOLINE FUEL

Test	Emissions (g/hp-hr)			BSFC (lb/hp-hr)
	HC	NO_x	CO	
Baseline 1	1.49	8.02	16.58	0.561
Baseline 2	1.48	8.61	16.07	0.597
Gasoline Mean	1.49	8.32	16.33	0.579

Two additional emissions tests were conducted on engine B using an LPG conversion kit. Mixture was set in accordance with the kit's instructions, which resulted in an A/F of 15.7 at full power. Table 43 summarizes the C2 cycle results. Compared to gasoline results, NO_x emissions increased 40 percent, while HC and CO emissions decreased 37 percent and 55 percent, respectively, due to the leaner calibration with the LPG system. Significantly lower fuel consumption was observed when the engine was equipped with the LPG conversion kit. This is due to leaner operation with LPG, and the higher energy density of LPG, which contains nine percent more energy on a mass basis than California Phase II gasoline.

TABLE 43. ENGINE B EMISSION RESULTS, ISO 8178-C2 CYCLE, LPG FUEL

Test	Emissions (g/hp-hr)			BSFC (lb/hp-hr)
	HC	NO_x	CO	
Baseline 1	0.97	11.04	8.08	0.526
Baseline 2	0.91	12.30	6.65	0.526
LPG Mean	0.94	11.67	7.37	0.526

c. Engine C

Engine C was equipped with a gasoline carburetor as received. It was tested using dilute procedures over the ISO 8178-C2 cycle. The engine was operated with both gasoline and LPG fuels. The governor was disabled prior to testing with gasoline. Table 44 summarizes the results from the steady-state emissions tests of engine C with gasoline fuel.

TABLE 44. ENGINE C EMISSION RESULTS, ISO 8178-C2 CYCLE, GASOLINE FUEL

Test	Emissions (g/hp-hr)			BSFC (lb/hp-hr)
	HC	NO_x	CO	
Baseline 1 Gasoline	3.75	7.77	47.8	0.611
Baseline 2 Gasoline	3.87	7.71	53.5	0.621
Gasoline Mean	3.81	7.74	50.7	0.616

Compared to the previously reported emission test results from engines A and B, engine C produced higher brake specific HC and CO, and was less fuel efficient. However, it produced lower NO_x. This indicates that engine C is calibrated richer than either engine A or B. Fuel efficiency is a good indicator of mixture calibration for the three engines tested, because as BSFC increases, HC and CO increase, and NO_x decreases. HC+NO_x totals are similar between these three engines, but the relative contribution of HC to HC+NO_x increases as BSFC increases.

Table 45 shows the results of three tests performed with LPG fuel on engine C. We decided to set the AFR at WOT to specification and perform testing in modes 1 through 5 without adjusting the mixture setting, and then to set the idle AFR to the correct setting. Following the first test, the AFR at WOT was not reset to specification, which made the engine operate rich. A full test was performed before the error was noted. The results of this test (Baseline 2) are included in Table 45 for completeness. The mean result was calculated using the first and third tests only.

TABLE 45. ENGINE C EMISSION RESULTS, ISO 8178-C2 CYCLE, LPG FUEL

Test	Emissions (g/hp-hr)			BSFC (lb/hp-hr)
	HC	NO_x	CO	
Baseline 1 LPG	1.70	11.6	7.09	0.54
Baseline 2 LPG[a]	2.55	6.30	84.5	0.58
Baseline 3 LPG	1.69	11.4	10.5	0.54
LPG Mean of Tests 1 and 3	1.70	11.5	8.80	0.54
[a] Mixture was incorrectly set rich for this test, data reported for completeness.				

d. Engine E

Engine E was equipped with a gasoline carburetor as received. It employs an older design and uses a rich calibration to promote cooler operation. It was tested using dilute procedures over the ISO 8178-C2 and D2 cycles. The engine control system governor was disabled prior to testing. Tables 46 and 47 summarize the results from the steady-state emissions tests of engine E with gasoline fuel using the C2 and D2 cycles, respectively.

TABLE 46. ENGINE E EMISSION RESULTS, ISO 8178-C2 CYCLE, GASOLINE FUEL

Test	Emissions (g/hp-hr)			BSFC (lb/hp-hr)
	HC	NO_x	CO	
Baseline 1	19.2	1.09	680	1.42
Baseline 2	18.2	1.03	687	1.44
C2 Mean	18.7	1.06	684	1.43

TABLE 47. ENGINE E EMISSION RESULTS, ISO 8178-D2 CYCLE, GASOLINE FUEL

Test	Emissions (g/hp-hr)			BSFC (lb/hp-hr)
	HC	NO_x	CO	
Baseline 1	10.7	1.68	483	1.10
Baseline 2	10.6	1.79	476	1.09
D2 Mean	10.6	1.74	479	1.10

e. Engine D

Engine D was equipped with a Zenith gasoline carburetor as received. It was tested using dilute procedures over the ISO 8178-C2 cycle on gasoline. The engine was then fitted with an LPG fuel system for D2 cycle tests. The governor was disabled prior to testing with gasoline. Tables 48 and 49 summarize results from steady-state emissions tests of engine D with gasoline over the C2 cycle, and LPG over the D2 cycle, respectively. The Zenith carburetor was calibrated richer than all other liquid-cooled engine carburetors, producing higher brake-specific HC and CO emissions, and lower NO_x emissions, than all other engines except engine E. However, C2 cycle HC+NO_x emissions were the lowest of all engines tested.

TABLE 48. ENGINE D EMISSION RESULTS, ISO 8178-C2 CYCLE, GASOLINE FUEL

Test	Emissions (g/hp-hr)			BSFC (lb/hp-hr)
	HC	NO_x	CO	
Baseline 1	4.08	5.28	126	0.679
Baseline 2	3.90	5.47	122	0.662
C2 Gasoline Mean	3.99	5.38	124	0.671

TABLE 49. ENGINE D EMISSION RESULTS, ISO 8178-D2 CYCLE, LPG FUEL

Test	Emissions (g/hp-hr)			BSFC (lb/hp-hr)
	HC	NO_x	CO	
Baseline 1	0.88	9.72	2.10	0.454
Baseline 2	0.90	10.0	2.05	0.455
D2 LPG Mean	0.89	9.86	2.08	0.455

f. Steady-State Test Results Summary

Summaries of baseline emission test results are reported below. Engine test results are listed in each table in order of increasing fuel consumption. Table 50 shows the emission levels of engine tests using the ISO 8178-C2 cycle on gasoline fuel. Species emission rates varied consistent with the classic directions associated with enleanment. That is, with enleanment hydrocarbons and carbon monoxide rates decreased, and oxides of nitrogen rates increased. Table 51 shows the emission levels of engine E tested using the ISO 8178-D2 cycle on gasoline fuel. Table 52 shows the emission levels of engines tests using the ISO 8178-C2 cycle on LPG fuel. Table 53 shows the emission levels of engine D tested using the ISO 8178-D2 cycle on LPG fuel.

TABLE 50. INDUSTRIAL ENGINE AVERAGE ISO 8178-C2 CYCLE EMISSIONS, GASOLINE FUEL

Industrial Engine	Emissions, g/hp-hr				BSFC, lb/hp-hr
	HC	NOx	HC+NOx	CO	
A	1.69	12.0	13.7	20.1	0.554
B	1.49	8.32	9.81	16.3	0.579
C	3.81	7.74	11.6	50.7	0.616
D	3.99	5.38	9.37	124	0.671
E	18.7	1.06	19.8	684	1.43
C2 Gasoline Average	5.94	6.89	12.8	179	0.770

TABLE 51. INDUSTRIAL ENGINE ISO 8178-D2 CYCLE EMISSIONS, GASOLINE FUEL

Industrial Engine	Emissions, g/hp-hr				BSFC, lb/hp-hr
	HC	NOx	HC+NOx	CO	
E	10.7	1.70	12.4	479	1.10

TABLE 52. INDUSTRIAL ENGINE AVERAGE ISO 8178-C2 CYCLE EMISSIONS, LPG FUEL

Industrial Engine	Emissions, g/hp-hr				BSFC, lb/hp-hr
	HC	NOx	HC+NOx	CO	
B	0.94	11.7	12.6	7.37	0.526
C	1.70	11.5	13.2	8.80	0.540
C2 LPG Average	1.32	11.6	12.9	8.09	0.533

TABLE 53. INDUSTRIAL ENGINE ISO 8178-D2 CYCLE EMISSIONS, LPG FUEL

Industrial Engine	Emissions, g/hp-hr				BSFC, lb/hp-hr
	HC	NOx	HC+NOx	CO	
D	0.89	9.86	10.8	2.08	0.455

4. Cold- and Hot-Start Test Results

a. Engine A

Although the cold-start procedure specified choked operation for only the first 30 seconds, engine A needed the choke engaged for the full 60 second idle period in order to remain running. This was not necessary during the hot-start. Averaged emissions from the cold- and hot-start tests on engine A are summarized in Table 54. Results are presented on both a mass (g/hr) and work-specific (g/hp-hr) basis. As expected with the enrichment caused by the choke, cold-start HC and CO emissions are considerably higher than from the warmed-up, steady-state C2 cycle. Cold-start NO_x emissions are less than C2 cycle levels. Hot-start HC and CO emissions, while substantially reduced from cold-start levels, are still significantly higher than C2 cycle levels due to both mode weighting and the presence of mode transitions.

TABLE 54. ENGINE A EMISSION RESULTS
COLD- AND HOT-START CYCLE, GASOLINE FUEL

Test	Mass Rate Emissions (g/hr)			Work-Specific Emissions (g/hp-hr)		
	HC	NO_x	CO	HC	NO_x	CO
Cold-Start	2070	157.8	1937	106	8.08	99.2
Hot-Start	113.4	201.0	861	5.46	9.68	41.5

The cold- and hot-start performance of engine A can be examined in more detail in Figures 5 and 6, which show HC, NO_x, and CO emissions on a second-by-second basis. HC and CO emissions were high at the start of both tests, but quickly dropped off as the engine was brought out of idle and into the first loaded point. Conversely, NO_x emissions started out low, but increased dramatically as engine speed and load were increased. Unlike steady-state test bag sample data which represents an averaged sample, data obtained from the continuous emissions monitoring system revealed considerable detail about the emissions associated with engine start-up. For example, the spikes that occurred near the 60 second point are due to throttle adjustments made to achieve targeted speed and load. Other emission effects are due to differences between the engine's throttle response and the characteristics of the electric dynamometer. For example, if the engine starts producing power before the dynamometer increases speed, then a positive torque spike develops. As the dynamometer catches up, torque quickly decreases back towards the intended target load. Even then, the load would sometimes overshoot the setpoint before finally settling at the intended level. This sequence of events caused the swings observed at 60 seconds in HC, NO_x, and CO emissions, as shown in Figure 5. Another aspect of this is seen in the NO_x trace during the cold-start. Throttle position settings required some fine tuning at 60 and 180 seconds to achieve target load values. These adjustments strongly affected NO_x emission levels.

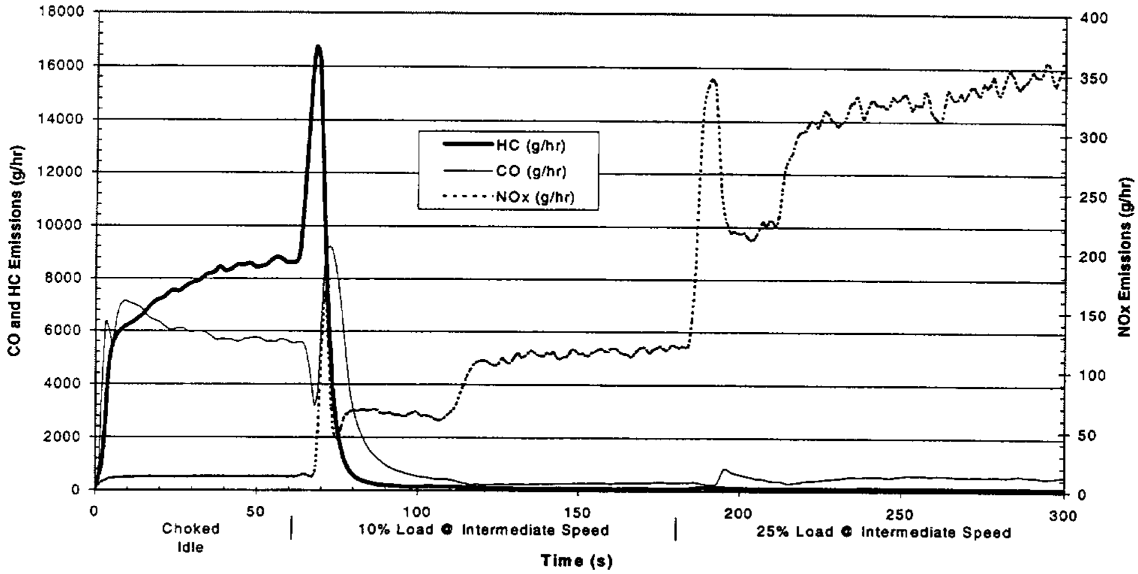

FIGURE 5. COLD-START EMISSIONS FOR ENGINE A GASOLINE FUEL

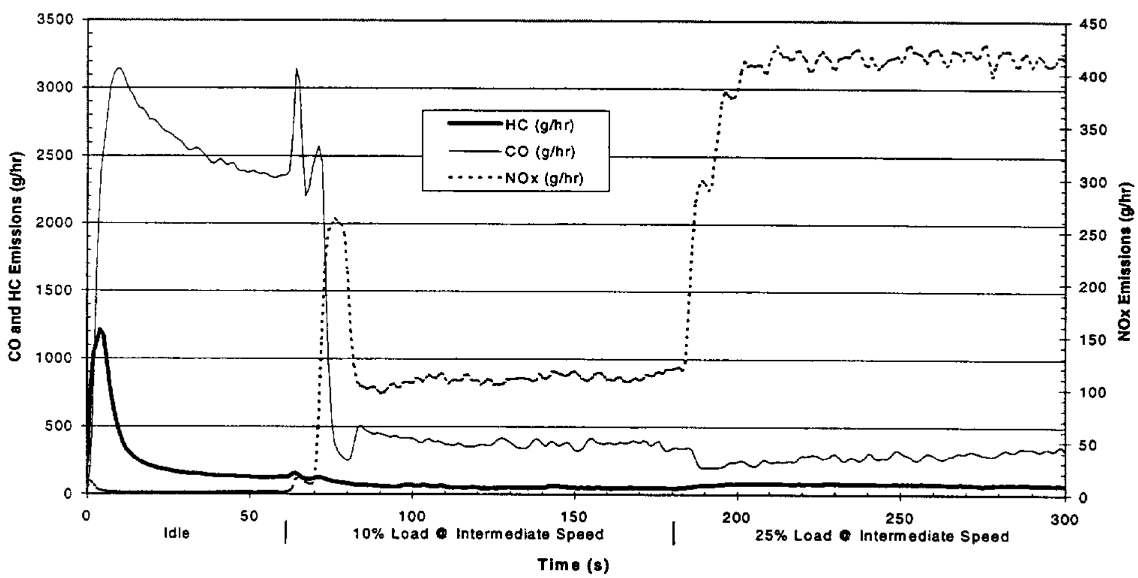

FIGURE 6. HOT-START EMISSIONS FOR ENGINE A GASOLINE FUEL

b. Engine B

Table 55 displays the cold- and hot-start results from engine B. Work-specific CO emissions were comparable to those observed with engine A, but neither test produced HC levels as high as observed with engine A. Engine B hot-start HC and CO emissions were 30 percent and 40 percent less, respectively, than those from the cold-start. Hot-start NO_x emissions were 10 percent higher than from the cold-start.

TABLE 55. ENGINE B EMISSION RESULTS COLD- AND HOT-START CYCLE, GASOLINE FUEL

Test	Mass Rate Emissions (g/hr)			Work-Specific Emissions (g/hp-hr)		
	HC	NO_x	CO	HC	NO_x	CO
Cold-Start	42.5	39.6	689	5.44	5.07	88.1
Hot-Start	29.5	43.5	409	3.64	5.37	50.6

Figures 7 and 8 exhibit the corresponding second-by-second emissions. Whereas a manual choke was used on engine A, engine B was equipped with an automatic choke. This was disengaged by briefly flipping the throttle open. However, this technique for disabling the choke also caused significant spikes in HC and CO, as seen at the 40 second mark of the cold-start cycle. Performance of engine B also differed from that of engine A in that more time was required for HC and CO emissions to diminish after coming off idle and into the 10 percent load point. It was not until approximately 160 seconds into the cold-start cycle and 130 seconds into the hot-start cycle that HC and CO emissions lined out.

As with engine A, variations in speed and load settings caused peaks in HC, NO_x, and CO emissions throughout the two tests. In particular, engine control difficulties during the first part of the hot-start (at around 13 seconds into the test) caused peaks in HC and CO. Additionally, the swings in NO_x emissions during the second minute of the hot-start cycle were due to the same types of problems experienced in the fourth minute of the engine A cold-start cycle.

c. Engine C

Engine C's carburetor was equipped with an automatic choke mechanism similar to the one on engine B. The choke was initially engaged by fully opening the throttle, thereafter a temperature sensitive bi-metallic strip gradually released the choke. Averaged emissions from engine C cold- and hot-start tests are shown in Table 56. Results are presented on both a mass (g/h) and work-specific (g/hp-h) basis. As expected with the enrichment caused by the choke, cold-start HC and CO emissions were considerably higher than from the hot-start test and from the warmed-up, steady-state C2 cycle. Cold- and hot-start NO_x emissions were less than C2 cycle levels. Hot-start HC and CO emissions, while substantially reduced from cold-start levels, were still significantly higher than C2 cycle levels.

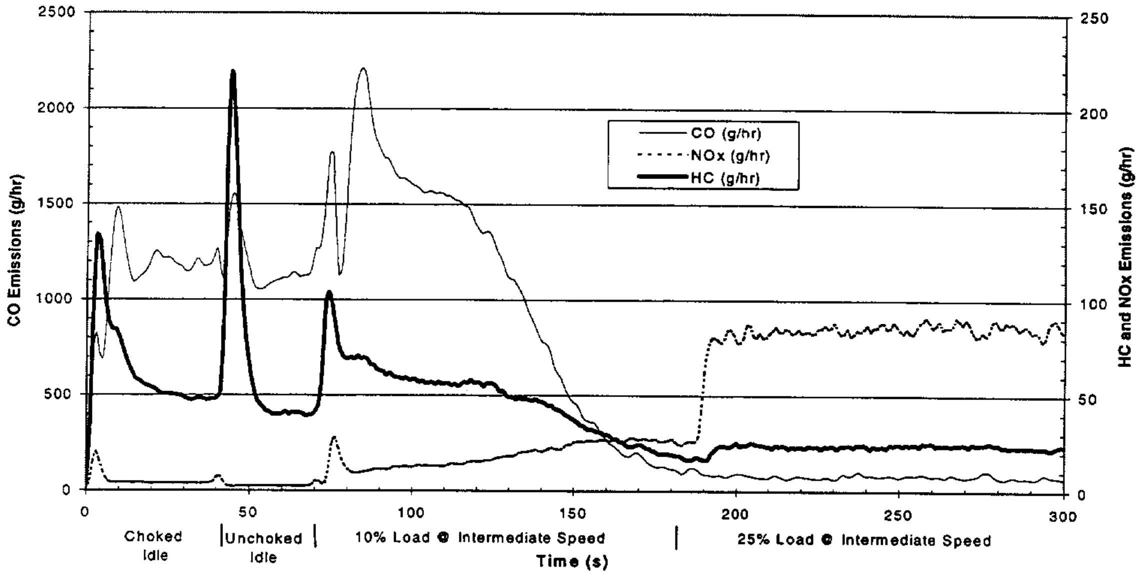

FIGURE 7. COLD-START EMISSIONS FOR ENGINE B - GASOLINE FUEL

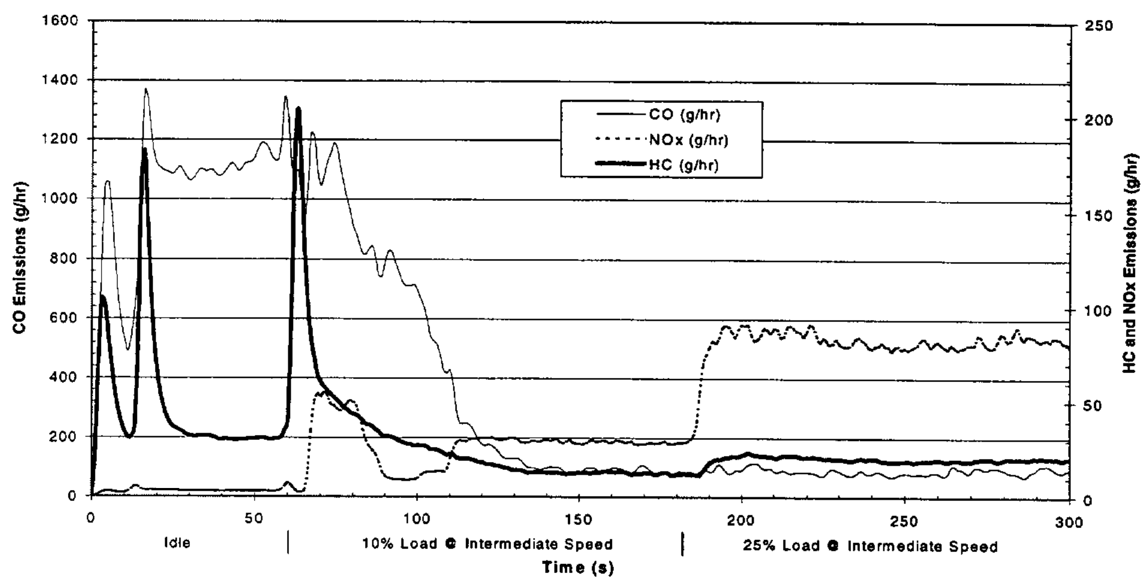

FIGURE 8. HOT-START EMISSIONS FOR ENGINE B - GASOLINE FUEL

TABLE 56. ENGINE C EMISSION RESULTS COLD- AND HOT-START CYCLE, GASOLINE FUEL

Test	Mass Emissions (g/hr)			Work-Specific Mass Emissions (g/hp-hr)		
	HC	NO_x	CO	HC	NO_x	CO
Cold-Start	86.9	25.2	1344	16.1	4.66	249
Hot-Start	45.0	35.9	325	9.16	7.32	66.1

The cold- and hot-start performance of engine C can be examined in more detail in Figures 9 and 10, which show HC, NO_x, and CO emissions on a second-by-second basis. HC and CO emissions peak at the start of both tests, but the choke kept HC and CO rates elevated much longer during the cold-start test. Conversely, NO_x emissions started out low, but increased dramatically as engine speed and load increased. As with the previous two engines, variations in speed and load settings caused peaks in HC, NO_x, and CO emissions throughout the two tests.

d. Engine E

Cold- and hot-start tests were conducted with engine E, and results are shown in Table 57. Graphical representations of cold- and hot-start emission rates from engine E are shown in Figures 11 and 12. The Zenith carburetor employed on the engine has a manual choke. Brake-specific cold start emissions of HC and CO were very high, and NO_x emissions were very low, owing to its rich calibration. Unlike the other engines tested, engine E's hot-start emissions were similar to its cold-start emissions.

TABLE 57. ENGINE E EMISSION RESULTS COLD- AND HOT-START CYCLE, GASOLINE FUEL

Test	Mass Emissions (g/hr)			Work-Specific Mass Emissions (g/hp-hr)		
	HC	NO_x	CO	HC	NO_x	CO
Cold-Start	359	5.80	5423	71.0	1.14	1071
Hot-Start	266	4.20	5360	57.5	0.91	1159

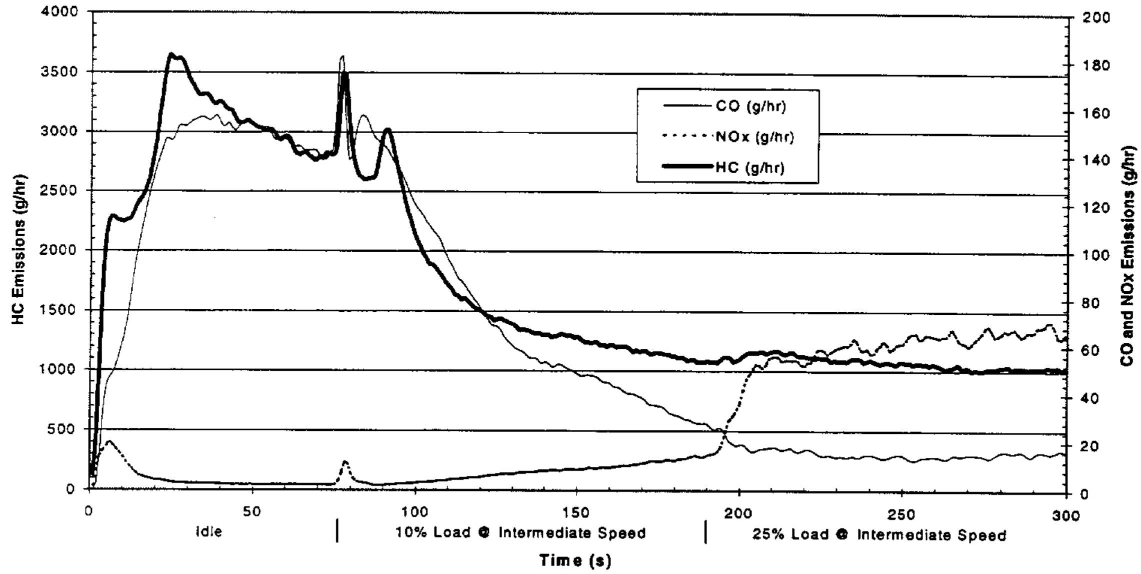

FIGURE 9. COLD-START EMISSIONS FOR ENGINE C - GASOLINE FUEL

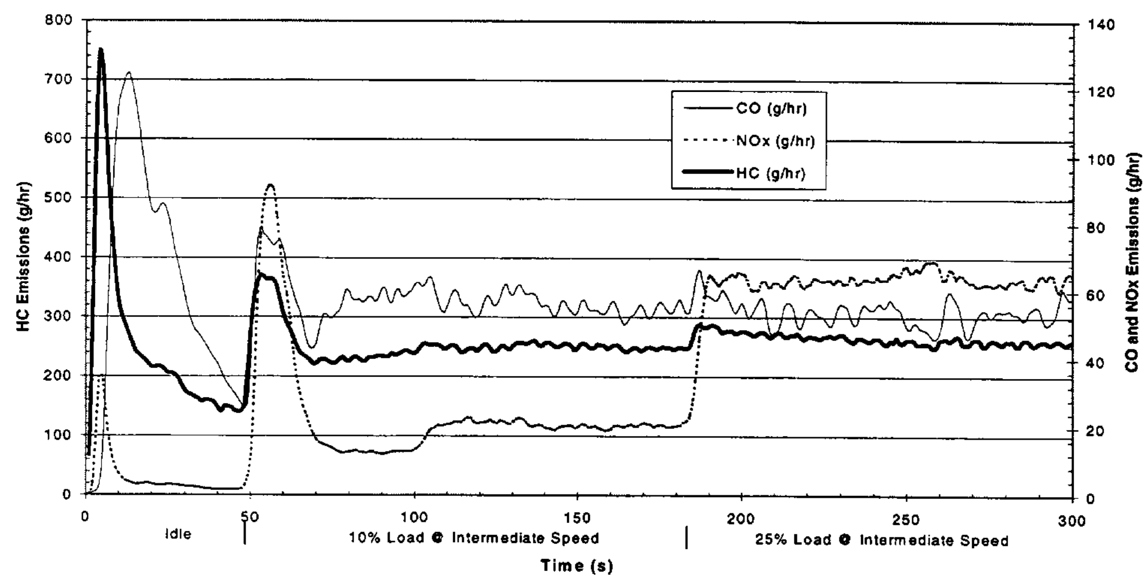

FIGURE 10. HOT-START EMISSIONS FOR ENGINE C - GASOLINE FUEL

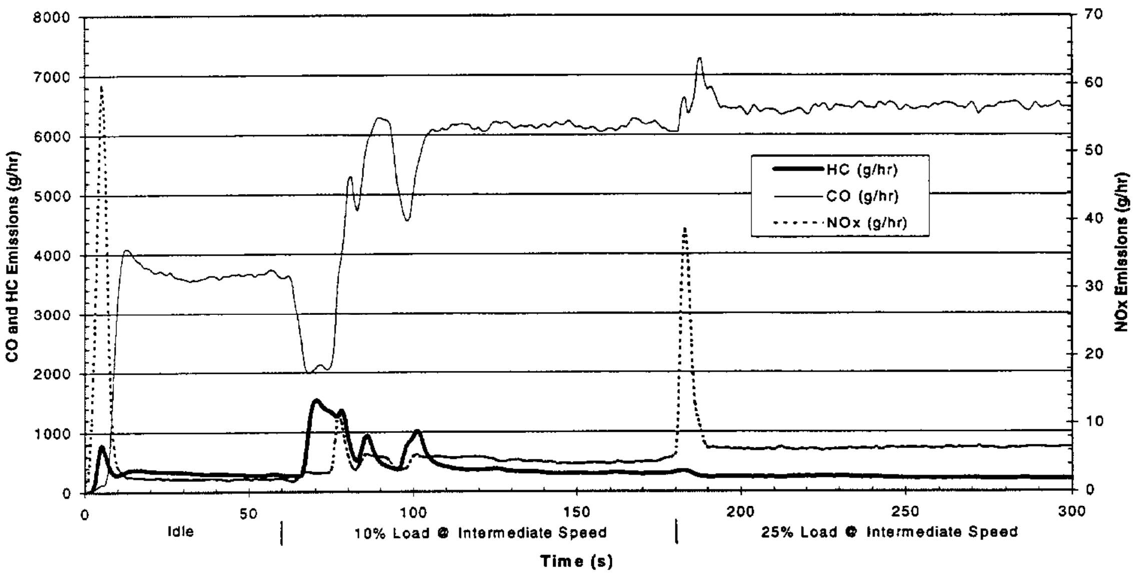

FIGURE 11. COLD-START EMISSIONS FOR ENGINE E - GASOLINE FUEL

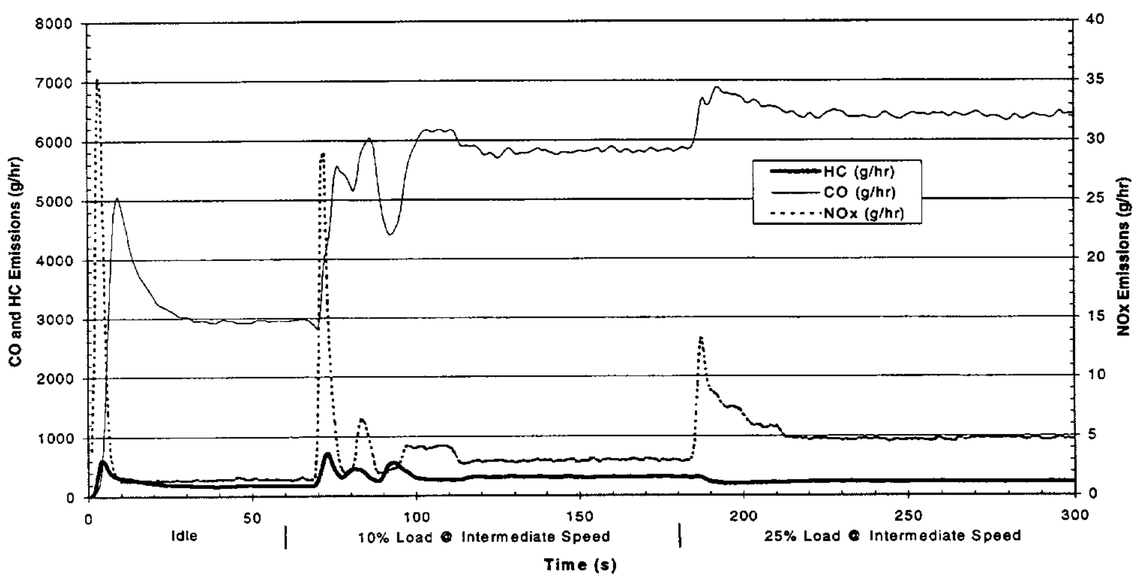

FIGURE 12. HOT-START EMISSIONS FOR ENGINE E - GASOLINE FUEL

e. Engine D

Cold- and hot-start tests were conducted with engine D with both gasoline and LPG. Results are shown in Tables 58 and 59 for gasoline and LPG, respectively. Graphical representations of the cold- and hot-start emission rates from engine D are shown in Figures 13 and 14. The Zenith carburetor on this engine has a manual choke. Duplicate gasoline start tests were conducted because during the first hot-start test, HC and CO emissions were higher, and NO_x emissions were lower than from the cold-start test, which was contrary to expectations. The second set of gasoline start test results reversed the order of HC emissions, but did not change the order of CO and NO_x emissions. We concluded that both tests are representative of starting behavior for this engine, and the reason for similar emissions between cold- and hot-starts may be due to the rich carburetor calibration, somewhat similar to engine E.

TABLE 58. ENGINE D EMISSION RESULTS COLD- AND HOT-START CYCLE, GASOLINE FUEL

Test	Mass Emissions (g/hr)			Work-Specific Mass Emissions (g/hp-hr)		
	HC	NO_x	CO	HC	NO_x	CO
Cold-Start 1	58.6	50.9	803	8.11	7.04	111
Hot-Start 1	72.1	32.3	946	11.2	5.00	147
Cold-Start 2	70.9	40.7	1006	10.5	6.04	149
Hot-Start 2	63.0	34.3	1079	8.72	4.75	150

TABLE 59. ENGINE D EMISSION RESULTS COLD- AND HOT-START CYCLE, LPG FUEL

Test	Mass Emissions (g/hr)			Work-Specific Mass Emissions (g/hp-hr)		
	HC	NO_x	CO	HC	NO_x	CO
Cold-Start	17.8	39.1	30.9	3.12	6.85	5.40
Hot-Start	15.2	32.9	32.4	2.67	5.79	5.70

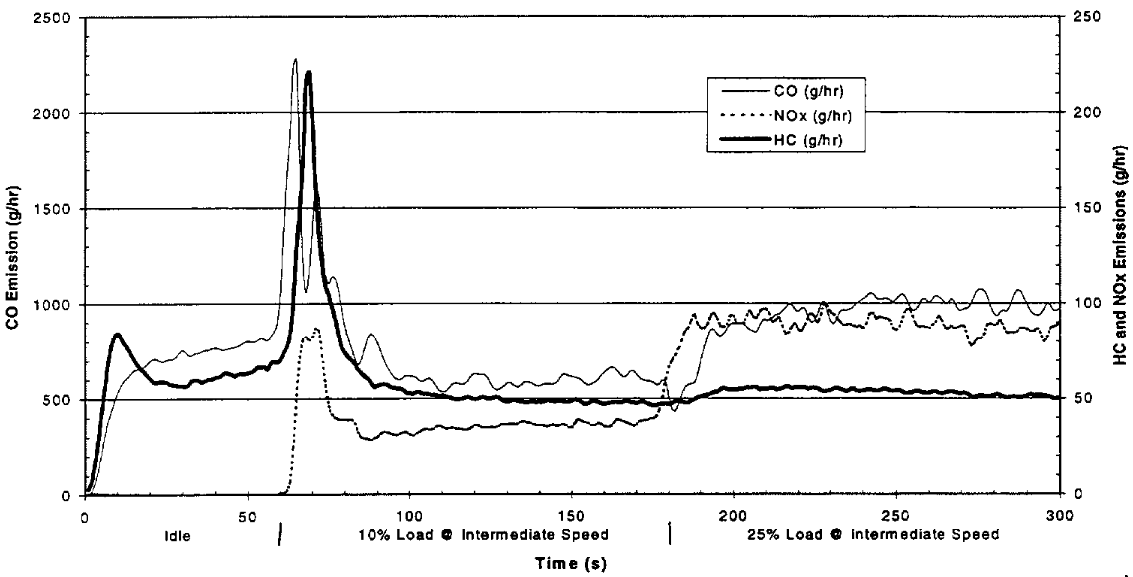

FIGURE 13. COLD-START EMISSIONS FOR ENGINE D - GASOLINE FUEL

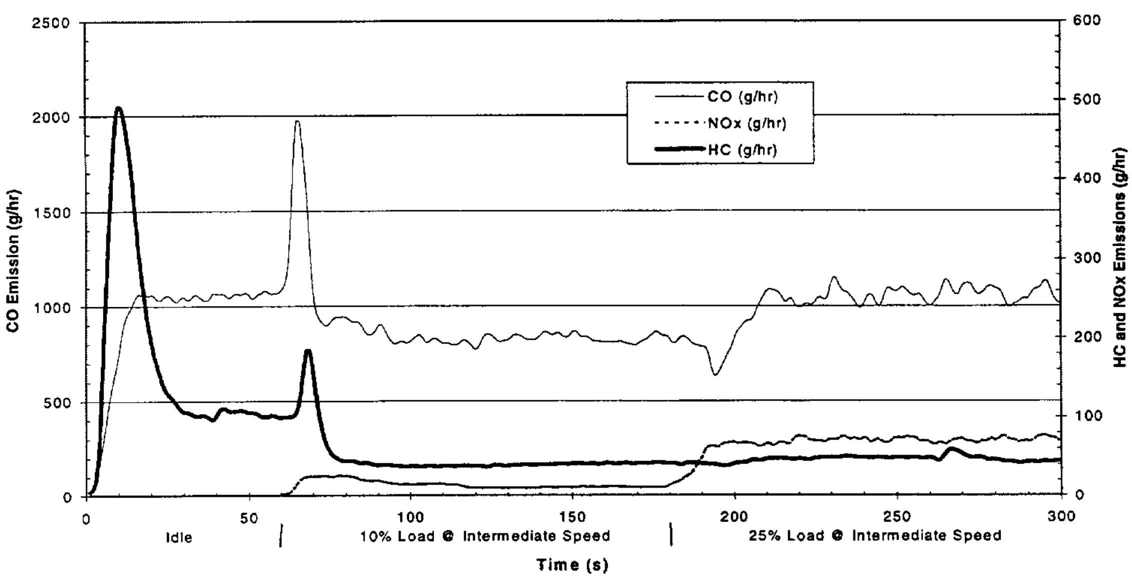

FIGURE 14. HOT-START EMISSIONS FOR ENGINE D - GASOLINE FUEL

Results with LPG fuel showed the advantages of leaner operation and lack of cold-start enrichment. Emissions of HC and CO were lower than during any other start tests. NO_x emissions were similar to engine D on gasoline, and to both engines B and C.

5. Baseline Tests with Unregulated Emissions Measurement

In addition to determination of criteria pollutants on the five baseline engines, ARB requested measurement of selected unregulated emissions on the two engines chosen for application of emission reduction technology. Separate baseline tests were performed on engines B and E to accommodate the special sampling equipment required for unregulated emissions measurement.

Unregulated emissions of formaldehyde, acetaldehyde, benzene, 1,3-butadiene, and styrene were measured on Engine B. Methane emissions were also measured. Hydrocarbon results are expressed as both HC (total hydrocarbons), and NMHC (non-methane hydrocarbons), which equals HC-CH_4 (methane). Results from the two tests are presented in Table 60.

TABLE 60. ENGINE B BASELINE EMISSION RESULTS ISO 8178-C2 CYCLE, LPG FUEL

Result	Test		
	Chem 1B	Chem 2B	Mean
Emissions, g/hp-hr			
HC	0.93	0.94	0.94
CH_4	0.03	0.03	0.03
NMHC	0.90	0.91	0.91
NOx	12.01	12.32	12.17
CO	4.32	4.72	4.52
NMHC+NOx	12.91	13.23	13.08
BSFC, lb/hp-hr	0.545	0.551	0.548
Emissions, mg/hp-hr			
Formaldehyde	86.5	85.8	85.7
Acetaldehyde	15.6	15.5	15.5
Benzene	0.4	0.5	0.4
1,3-butadiene	1.5	1.4	1.4
Styrene	0.0	0.0	0.0

Baseline and unregulated emissions were also measured on Engine E. These are presented in Tables 61 and 62.

TABLE 61. ENGINE E BASELINE EMISSION RESULTS ISO 8178-C2 CYCLE, GASOLINE FUEL

Result	Test		
	Chem 1E-C2	Chem 2E-C2	Mean
Emissions, g/hp-hr			
HC	15.12	15.18	15.15
CH_4	2.54	2.47	2.51
NMHC	12.40	12.54	12.47
NOx	1.35	1.25	1.30
CO	580.7	598.8	589.8
NMHC+NOx	13.75	13.79	13.77
BSFC, lb/hp-hr	1.29	1.31	1.30
Emissions, mg/hp-hr			
Formaldehyde	134.2	127.3	130.8
Acetaldehyde	12.9	12.2	12.6
Benzene	502.9	525.2	514.1
1,3-butadiene	90.0	91.2	90.6
Styrene	60.8	62.1	61.4

TABLE 62. ENGINE E BASELINE EMISSION RESULTS ISO 8178-D2 CYCLE, GASOLINE FUEL

Result	Test		
	Chem 1E-D2	Chem 2E-D2	Mean
Emissions, g/hp-hr			
HC	9.83	9.90	9.86
CH_4	1.61	1.49	1.55
NMHC	8.11	8.31	8.21
NOx	1.65	1.66	1.65
CO	444.6	453.6	449.1
NMHC+NOx	9.76	9.97	9.86
BSFC, lb/hp-hr	1.04	1.06	1.05
Emissions, mg/hp-hr			
Formaldehyde	96.9	85.9	91.4
Acetaldehyde	9.9	8.8	9.3
Benzene	370.7	376.4	373.6
1,3-butadiene	69.8	64.4	67.1
Styrene	45.6	44.5	45.1

SwRI used the Auto/Oil hydrocarbon speciation procedure to perform these analyses. This procedure was cooperatively developed by a consortia of automobile manufacturers and petroleum products companies. It uses three gas chromatographs to separate and identify several hundred individual hydrocarbon species that may be present in engine exhaust. While not required under this contract, this additional information was developed in the course of measuring the five species listed above. Complete, detailed modal emissions and speciation results are included in Appendix. B.

These results are different from the Engine E baseline results reported in Tables 46 and 47. The earlier tests were run using the manufacturer's recommended intermediate speed of 1600 rpm. However, for the durability demonstration as a pump drive, the manufacturer recommended a rated speed of 1800 rpm be used. Thus, the results reported in Tables 61 and 62 were determined using an intermediate speed of 1800 rpm for the C2 cycle and a rated speed of 1800 rpm for the D2 cycle. Note that only two seven-mode tests were run (Chem 1E and 2E). Results were recalculated using D2 cycle weight factors to generate the D2 cycle results.

B. Task 2.2 - Design of Emission-Controlled Gasoline/LPG Systems

1. Emission Reduction Engines

CARB chose two engines for emission reduction efforts - engines B and E. Baseline emissions from both engines were reported in Section III.A.

2. Gasoline Fuel Emission Reduction Systems

Zenith Fuel Systems agreed to support the emission reduction efforts in this project and provided considerable information regarding their Zenith Electronic Engine Management System (ZEEMS). The ZEEMS system offers control of both fuel delivery and ignition timing, if a distributor-less ignition system (DIS) is available. We initially planned to adapt a DIS from a four-cylinder automotive engine to engine E to enable this feature, although these plans were later changed due to problems with equipment availability.

a. Zenith Electronic Engine Management System (ZEEMS)

(1) Major System Components

The ZEEMS is a throttle body injection (TBI) fuel control system which incorporates an electronic throttle actuator into an aluminum throttle body. The ZEEMS system is a drive-by-wire system with throttle position controlled by the ECU based on input from the operator's pedal. The system does not require a mechanical throttle linkage.

Figure 15 is a photograph of the throttle body. Figure 16 is a cutaway drawing of the throttle body viewed along the axis of the throttle shaft, which is in the lower portion of the figure. Air intake is from the right of the figure, and the fuel injector is at the center top. Figure 17 is a cutaway drawing of the lower portion of the throttle body viewed perpendicular to the throttle shaft from behind the air intake. The figure shows the throttle actuator at lower right, the fuel pressure regulator at upper right, and the throttle plate at lower left.

A fuel pressure regulator is built into the throttle body which maintains 10 psi gasoline pressure at the injector. Unused gasoline is returned to the fuel tank. The ZEEMS system can also be configured for LPG or NG fuel, or as a dual fuel system. Gaseous fuel pressure is maintained at 24 psi at the injector. Dual fuel systems have an injector for each fuel in the throttle body.

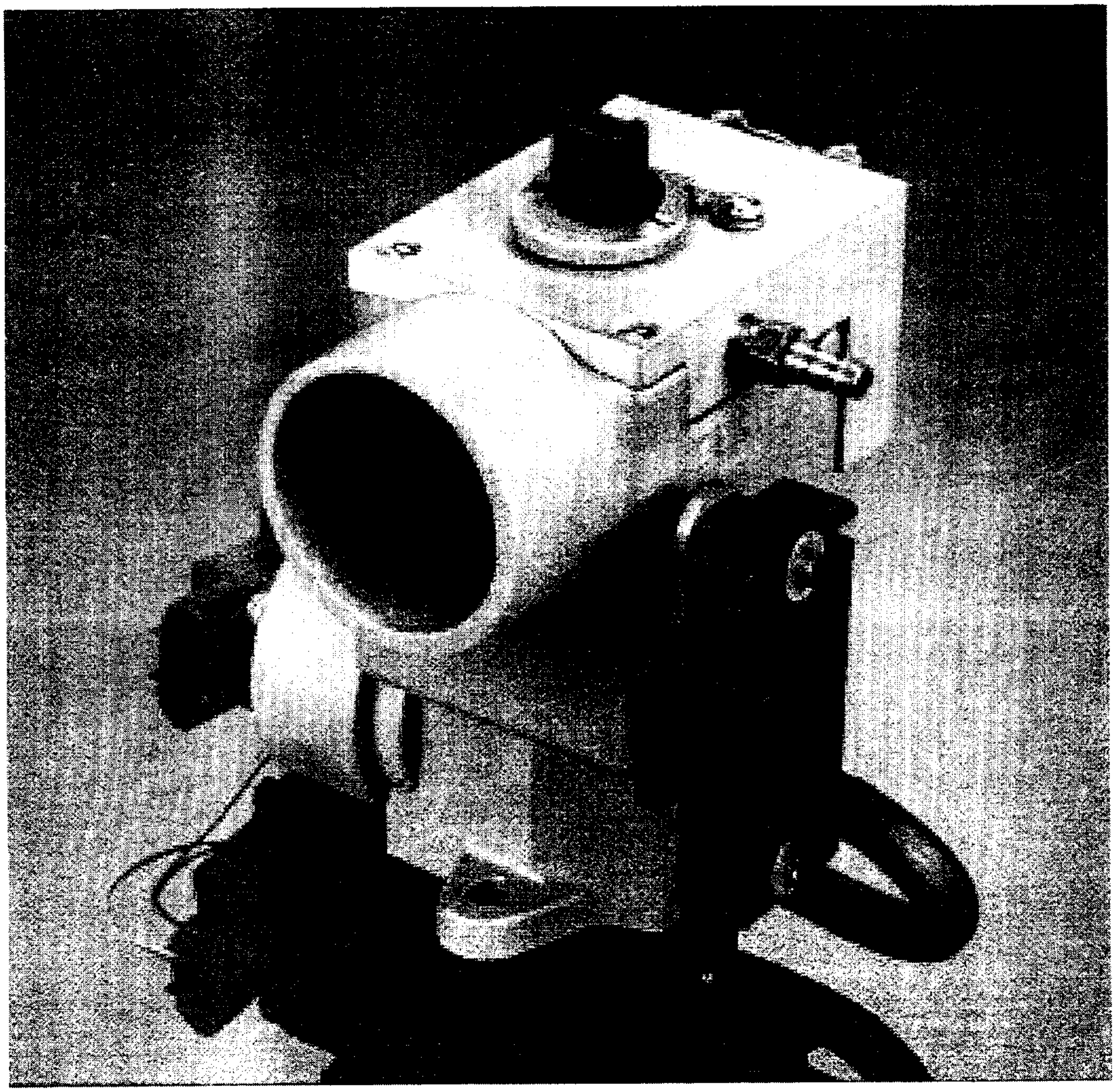

FIGURE 15. ZENITH THROTTLE BODY

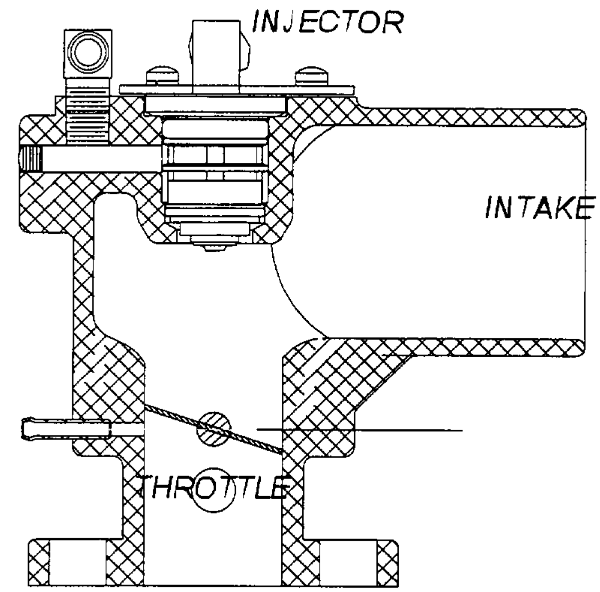

FIGURE 16. FIRST CUTAWAY VIEW OF ZENITH THROTTLE BODY

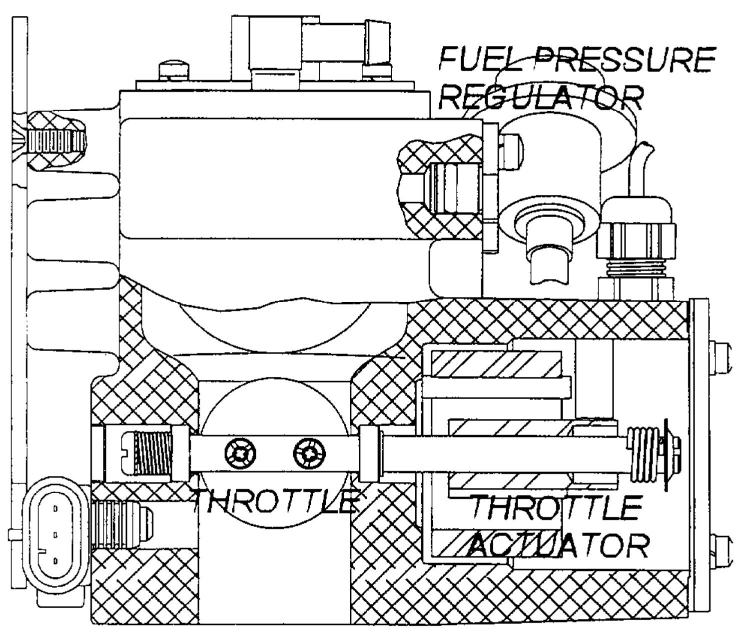

FIGURE 17. SECOND CUTAWAY VIEW OF ZENITH THROTTLE BODY

The other major components include an electric fuel pump, wiring harness, and engine control unit (ECU). Figure 18 is a schematic diagram of the ZEEMS. The fuel pump is rated for 6,000 hours operation. Sensors which are read to adjust fuel control include exhaust gas oxygen (EGO), engine temperature, intake air temperature, manifold air pressure, and speed. The speed sensor circuitry in the ECU can be configured to measure speed using either the spark signal or a magnetic pickup. If the engine has a distributor, the engine speed is measured from the spark signal.

The programmable ECU allows the system to be adapted to many different engines and applications. Through control of the throttle position, the ECU can act as an overspeed governor. Idle speed and up to three set speeds can be programmed into the ECU for fixed-speed applications, such as generators and pumps. Operator controlled switches can then be connected to select engine speed. Engines can also be derated to suit the needs of the OEM.

The ECU also controls the fuel pump relay or gaseous fuel lock-off valve to prevent engine runaway. Throttle actuation gain can be tailored to optimize throttle opening and closing which impacts engine driveability and emissions. The complete system is also tamper-proof as end users cannot program the ECU. Reprogramming is accomplished through a serial interface to a PC with the use of proprietary software. Once an engine control system calibration is complete, programs can be 'burned' into chips to further reduce the possibility of tampering.

(2) Fuel Injection System Design

The throttle body is designed to be compact to ease packaging concerns in equipment. Because fuel injection is digitally controlled, the fuel control system hardware is simpler, and fuel control calibrations are much easier to develop and much more precise than with analog carburetors. The ZEEMS system was designed to incorporate off-the-shelf sensor technology from automotive applications, thus reducing costs. Governing and ignition timing control on distributor-less ignition systems are integrally incorporated into one ECU. All the electronic components are sealed and ruggedized to withstand harsh operating environments.

(3) Design for Emission Control

The ZEEMS design was developed to meet upcoming industrial engine emission standards. Provisions were included in software and hardware to incorporate control of exhaust gas recirculation (EGR), and the use of an EGO sensor, which enables tight air/fuel ratio control about stoichiometry to promote high catalytic converter emission reduction efficiencies. Under open-loop control, the ECU accesses a fueling map of injector pulse width settings. The injection map is an eight by ten matrix of manifold vacuum and engine speed, respectively. In case of EGO sensor failure, the system reverts to open-loop control and uses the fuel injection map.

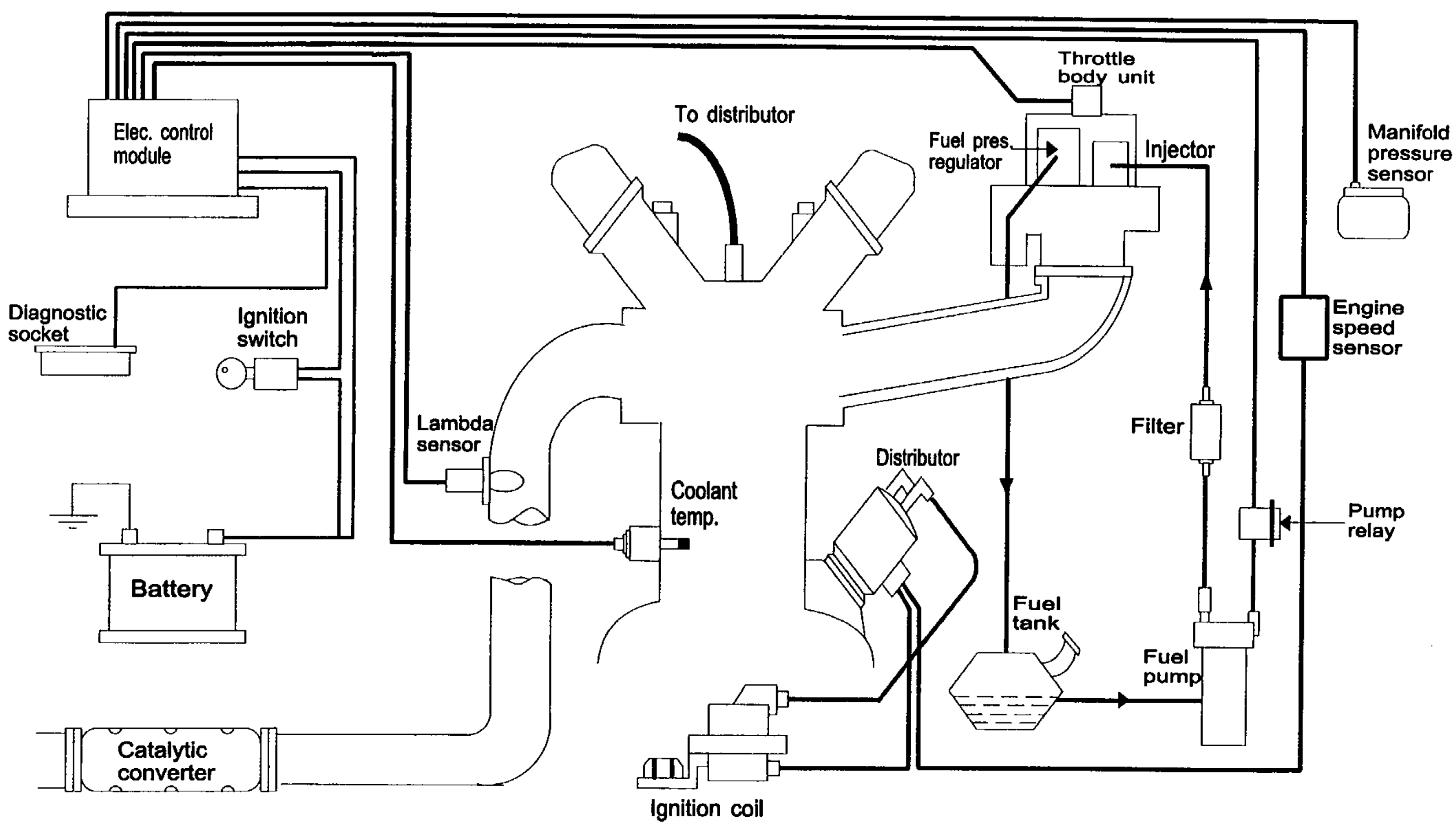

FIGURE 18. SCHEMATIC OF ZENITH ELECTRONIC ENGINE MANAGEMENT SYSTEM (ZEEMS)

Under closed-loop control, the fuel injection map is accessed for an initial fuel flow setting every time the engine speed or manifold vacuum changes enough to move into another row or column of the injection map. The ECU reads speed and manifold vacuum every revolution and compares the readings to its previous reading to see if engine operation has changed. If it has not changed, the ECU then reads the EGO sensor and adjusts fuel flow towards stoichiometry.

Sufficient memory storage capacity was included to allow fuel and ignition control maps for two fuels. The system also automatically compensates for altitude changes. Benefits of using the ZEEMS system include better exhaust emission control, and improved fuel economy. Also, the system provides superior cold- and hot-start performance without the use of a choke, by using programmed enrichment strategies. The system also eliminates engine dieseling on shutdown.

b. Distributor-less Ignition System

Another benefit of the ZEEMS system is the ability to better control ignition timing. By adapting a distributor-less ignition system, the ZEEMS can be calibrated to reduce emissions throughout the operational range of the engine. For distributor-less ignition systems, a magnetic pickup is used, which senses a 36-minus-1 tooth gear on the crankshaft. The gear is aligned on the crankshaft such that the missing tooth signals a known advance from cylinder one top dead center, as it passes the magnetic pickup.

The ignition timing map in the ZEEMS software is a two-dimensional matrix of ignition timing as a function of engine speed and manifold pressure. Ignition advance settings between setpoints of the ignition matrix are linearly interpolated from surrounding setpoints. In addition, ignition setting can be advanced or retarded based on programmed functions of engine temperature, intake air temperature, and rate of change of manifold pressure.

3. LPG Fuel Emission Reduction Systems

Both of the gaseous fuel control system manufacturers on the Technical Advisory Committee offered closed-loop control systems and supporting expertise to the emission reduction efforts of this project. This section describes open-loop and closed-loop control systems. Three closed-loop (CL) LPG systems are discussed, and figures showing hardware and fuel system schematics are provided. Finally, we recommend a strategy to identify an LPG closed-loop fuel control system to achieve the emission reduction goals of the project.

a. LPG Open-Loop Fuel System

(1) Air-Gas Valve Carburetor

Mixers are air-gas valve carburetors which meter air and fuel in response to engine speed and throttle position. Figure 19 shows a simplified schematic of an air valve carburetor attached to an engine. Cranking the engine lowers pressure in the intake manifold as the piston descends. Through passages (P) in the air valve, lowered pressure is communicated to the upper side of the diaphragm (D). As a result, the diaphragm lifts against the downward pressure of the metering spring (S), and as part of the assembly, the gas metering valve (V) is lifted off its seat.

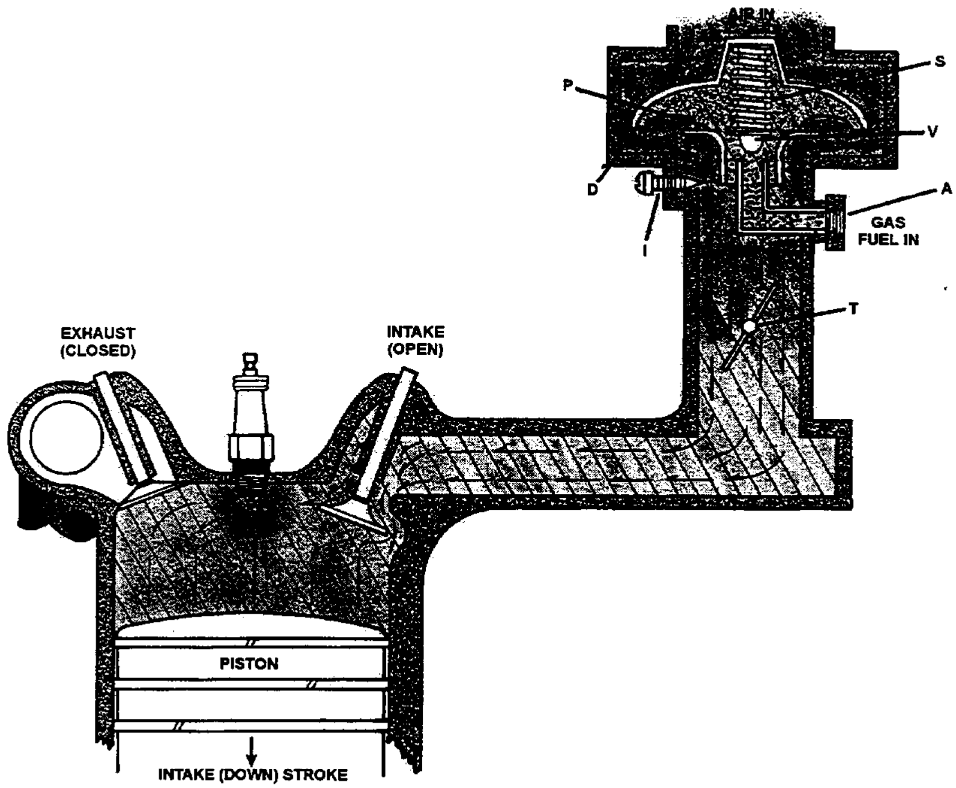

FIGURE 19. AIR-GAS VALVE CARBURETION SYSTEM

Approximately 0.2 psi (6" w.c.) of pressure is required to lift the air valve off its seat. Approximately 0.5 psi (13.8 w.c.) lifts the valve to the top of its travel in full open position. Lowered pressure communicated to the top of the diaphragm varies with engine speed and position of the throttle valve opening (T). The air valve assembly meters the air flow into the engine by moving precisely in response to the demands of the engine and throttle valve position. The controlled pressure drop of 0.2 to 0.5 psi set up by the metering spring provides the signal or force necessary to draw fuel into the air stream within the carburetor. The gas metering valve (V) is attached to the air valve assembly and is shaped to admit the correct amount of fuel from the gas jet to mix with incoming air at any opening of the air valve.

There are two mixture adjustments, at idle and at full load. The total volume of air and fuel passing the closed throttle at idle is constant. The idle adjustment bypasses a portion of incoming air around the air valve opening. As the idle adjustment is opened, the air valve partially closes, thereby closing the gas metering valve and leaning the idle air-fuel mixture. The power mixture adjustment controls mixtures when the gas metering valve is fully withdrawn from the jet. This adjustment is effective only when the engine approaches full-load condition, and can be set only with the engine loaded, at or close to its rated speed.

Mixtures between idle and full-load conditions are controlled by the shape of the gas metering valve. The gas metering valve is shaped to produce lean mixtures at light loads and increasingly rich mixtures at heavier loads and higher engine speeds. The gas valve is shaped to provide optimum mixtures for the "mid-size engine," between the largest and smallest displacement engine upon which the carburetor will be installed. Figure 20 is a dimensionally correct drawing of an updraft type carburetor.

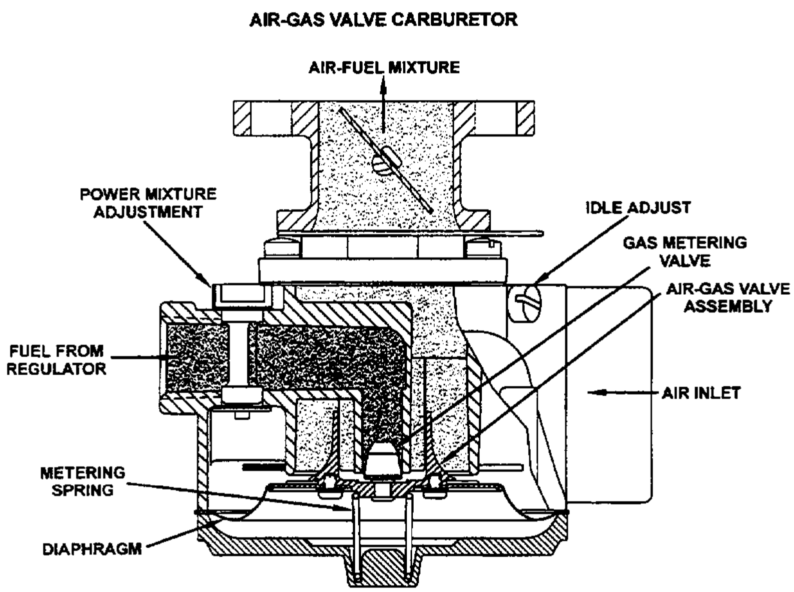

FIGURE 20. UPDRAFT CARBURETOR

(2) Fuel Pressure Regulator

Figure 21 shows a two stage pressure regulator and converter. Liquid propane enters the pressure regulator through the fuel inlet port. It then flows past the primary valve (the primary valve is normally open) into the primary chamber. The pressure signal travels through a port into the primary diaphragm chamber. The pressure in the primary diaphragm chamber forces the primary diaphragm to pivot against the primary valve pin, and move it toward the primary valve. Movement of the primary diaphragm closes the primary valve pin against its seat, stopping fuel flow into the regulator. The liquid fuel, under pressure entering the regulator, is heated and expanded to a vapor by engine coolant, which also prevents freezing as the liquid expands.

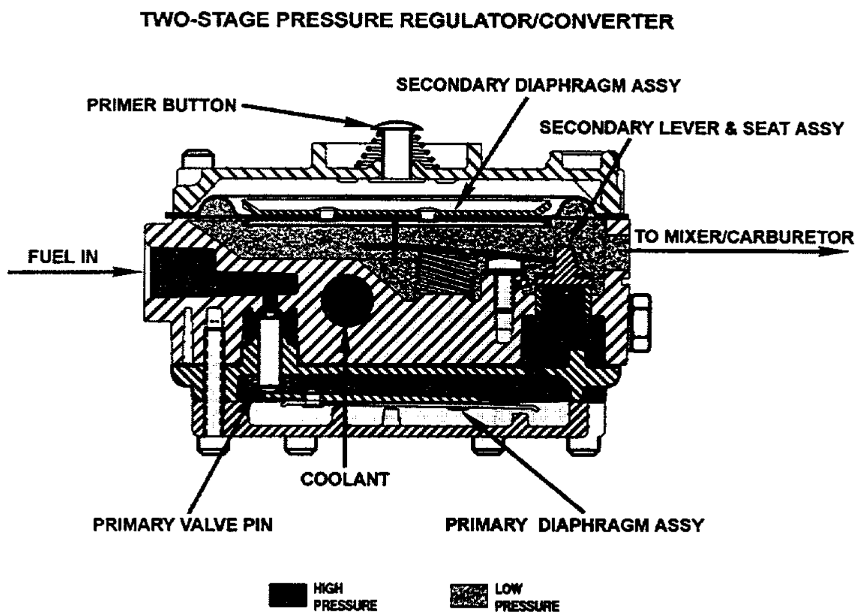

FIGURE 21. TWO-STAGE PRESSURE REGULATOR AND CONVERTER

A negative pressure signal travels from the mixer (carburetor) to the secondary chamber of the pressure regulator. Because of the negative pressure, atmospheric pressure forces down the secondary diaphragm assembly. This movement opens the secondary lever and seat assembly allowing fuel to flow to the mixer. Part of the pressure differential is satisfied as fuel flows and the secondary diaphragm moves the secondary seat to adjust the flow.

(3) Vacuum Fuel Lock

The air valve carburetor can not positively shut off fuel flow when the engine stops. To prevent fuel from leaking out when the engine is shut off, vacuum fuel locks are utilized to positively stop fuel flow. Figure 22 shows the workings of a vacuum fuel lock. Vacuum fuel locks are normally closed. They use vacuum from below the air valve mixer to open the fuel lock. If the engine stops or is turned off, engine vacuum dissipates and the fuel lock closes automatically. When the engine is cranking or running, air valve vacuum is transmitted from the mixer to the fuel lock through a vacuum hose. The vacuum acts upon the diaphragm assembly, pulling it inward against the valve operating lever. As the valve operating lever is depressed, it moves the valve operating pin which lifts the valve off of its seat. This allows propane to flow through the fuel lock's 10 micron filter and on to the pressure regulator. Figure 23 shows the complete fuel system including fuel tank.

VACUUM FUEL LOCK

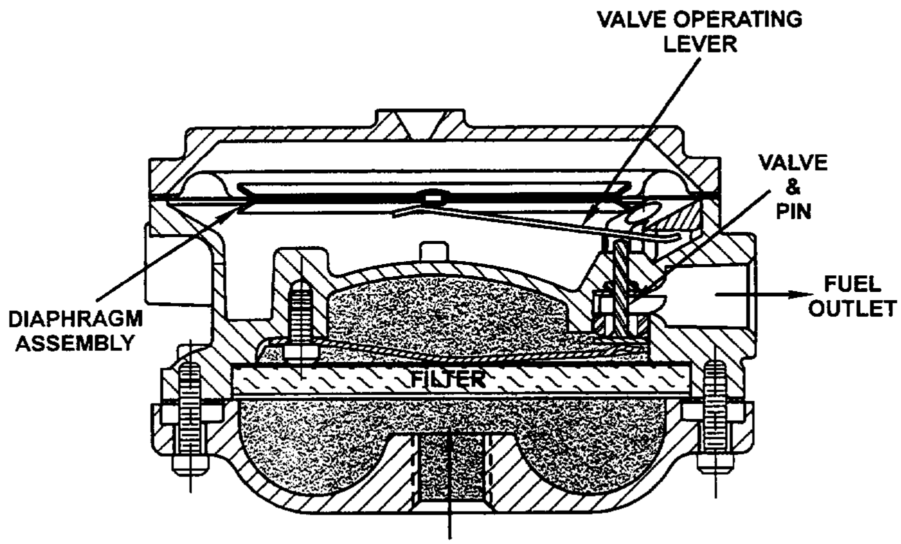

FIGURE 22. VACUUM FUEL LOCK

b. LPG Closed-Loop Fuel Systems

One manufacturer has designed and manufactured three electronic closed-loop fuel controllers for use with LPG, CNG, and LNG gaseous fuel systems. Feedback information from an EGO (exhaust gas oxygen) sensor is used to regulate the fuel mixture, which corrects to the stoichiometric air/fuel ratios of different fuels and for different engine operating modes. These controllers can also use engine MAP (manifold absolute pressure) sensors, and engine speed input to target stoichiometric.

(1) First Closed-Loop Control System

The first system is a digital closed-loop fuel controller for alternative fuels. Its electronic control package is compact, of rugged construction, and hermetically sealed to survive harsh operating environments. It uses an 8-bit microprocessor which reads sensors and produces a fuel control signal at 100 Hz. In open-loop mode, it can also control an air pump diverter to regulate air injection into the exhaust manifold ahead of an oxidation catalyst.

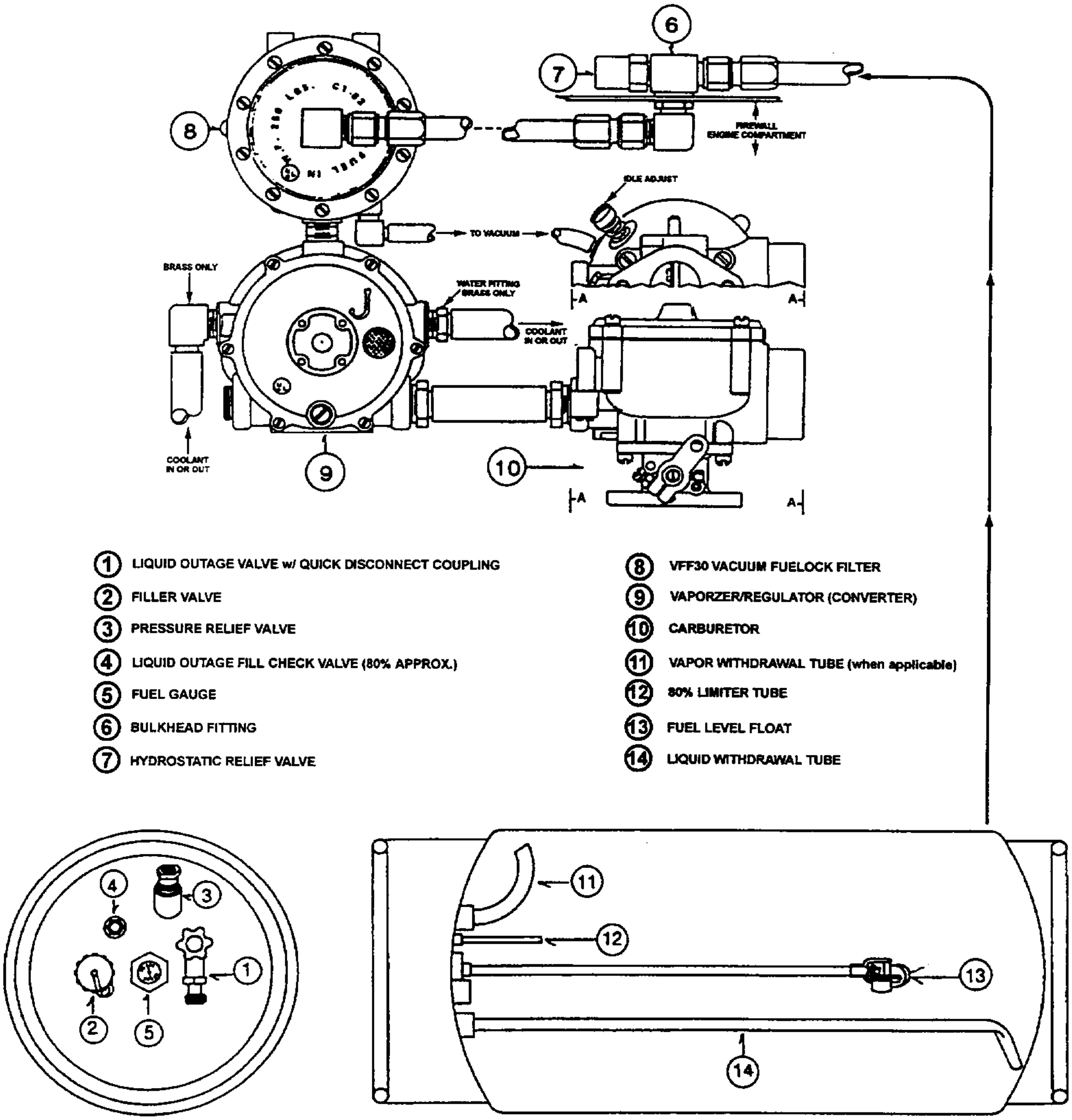

FIGURE 23. OPEN-LOOP LPG FUEL SYSTEM

The normal open-loop fuel pressure regulator described previously is replaced with one which can be regulated by the system controller to control fuel delivery. Regulator pressure is controlled by a fuel control valve (FCV). Figure 24 shows the externally controllable pressure regulator. The FCV (1) is connected between the atmospheric side of the regulator secondary diaphragm (2) and the air valve venturi of the mixer. The FCV is a solenoid controlled valve which receives signals from the electronic controller, changing its duty cycle. By changing the duty cycle, venturi vacuum increases or decreases on the atmospheric side of the secondary diaphragm of the regulator. This change in vacuum causes the regulator to increase or decrease the fuel supply to the mixer. The atmospheric vent orifice (3) allows for the depletion of vacuum over the diaphragm and a controlled bleed for dynamic response of the diaphragm.

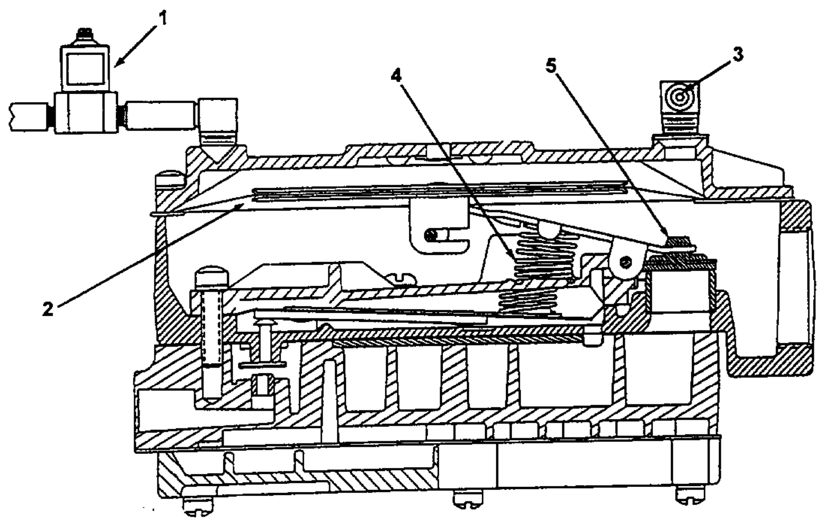

FIGURE 24. CLOSED-LOOP SYSTEM FUEL PRESSURE REGULATOR

The closed-loop fuel pressure system is constantly targeting stoichiometric air/fuel mixture. The mixers are calibrated to provide a rich mixture, and the fuel mixture is enleaned with the variable vacuum signal. When the EGO sensor sends a voltage above 500 mv, the controller interprets that the fuel mixture is rich, and increases the duty cycle of the fuel valve, allowing more air valve vacuum to act on the top side of the secondary diaphragm. The increased vacuum counteracts the secondary spring (4) pressure, and closes the secondary valve (5), which slightly reduces the flow of fuel from the regulator. The more vacuum, the lower the fuel pressure.

When the EGO sensor sends a voltage less than 500 mv, it signals to the controller that the mixture is now lean. The controller will decrease the duty cycle of the FCV, lowering the amount of air valve vacuum acting on the top side of the secondary diaphragm. Spring pressure then moves the diaphragm, which opens the secondary valve and allows more fuel to flow.

(2) Second Closed-Loop Control System

The second closed-loop control system expands on the simple logic of the first system by using a lookup table to choose a duty cycle for the FCV before the EGO sensor responds to a change in air/fuel ratio. The second system uses a manifold absolute pressure (MAP) sensor and an engine speed sensor as inputs to a three-by-three table from which the duty cycle is chosen, and then fine-tuned by EGO feedback. During the initial few minutes that power is applied to the control module, it stores the duty cycle found at stoichiometric in the lookup table. By taking the engine to its limits of load and speed and allowing the air/fuel ratio to reach stoichiometric, the full lookup table is produced. For the first 24 minutes, the table is updated at a high frequency; thereafter the table is updated slower. Figure 25 is a schematic of this closed-loop fuel control system adapted to engine B.

The second system thus reaches stoichiometric quicker than the first system. It also continuously compensates for changes in the total fuel system due to wear and component aging. In addition, it will re-program the lookup table to adjust the duty cycle if the LPG fuel mix changes. During transient engine operation, the lookup table approach keeps the air/fuel ratio closer to stoichiometric than the first system.

(3) Third Closed-Loop Fuel Control System

The third system's electronic control module uses engine speed and an EGO sensor as input. The ECM can be programmed to adjust the rate at which the duty cycle is updated, as well as the magnitude of the change to the FCV duty cycle depending on engine speed. While at idle, the control system stores the FCV stoichiometric duty cycle in memory to aid in start-up and closed-throttle engine operation. The stoichiometric switch point can be changed to bias the air/fuel ratio slightly lean or rich of stoichiometric, or to compensate for differences in the control speed (time constant) correction to stoichiometric, when enleanment or enrichment is needed. The ability to bias air/fuel ratio is extremely helpful in matching exhaust gas character to differing catalyst formulations.

4. Emission Control System Development

SwRI developed emission control systems on Engines B and E. The continuous emission rate measurement system, which was used to quantify engine start emissions during the baseline tests, was the primary developmental tool. It enabled us to quickly determine optimal emission levels as adjustments were made to fuel and ignition settings.

Developmental efforts were focused on achieving the following:

- Tight closed-loop control of air/fuel ratio
- Optimization of ignition timing settings
- Acceptable engine response
- Identification of catalytic converter with necessary reduction efficiencies
- Integration of emission control hardware into equipment.

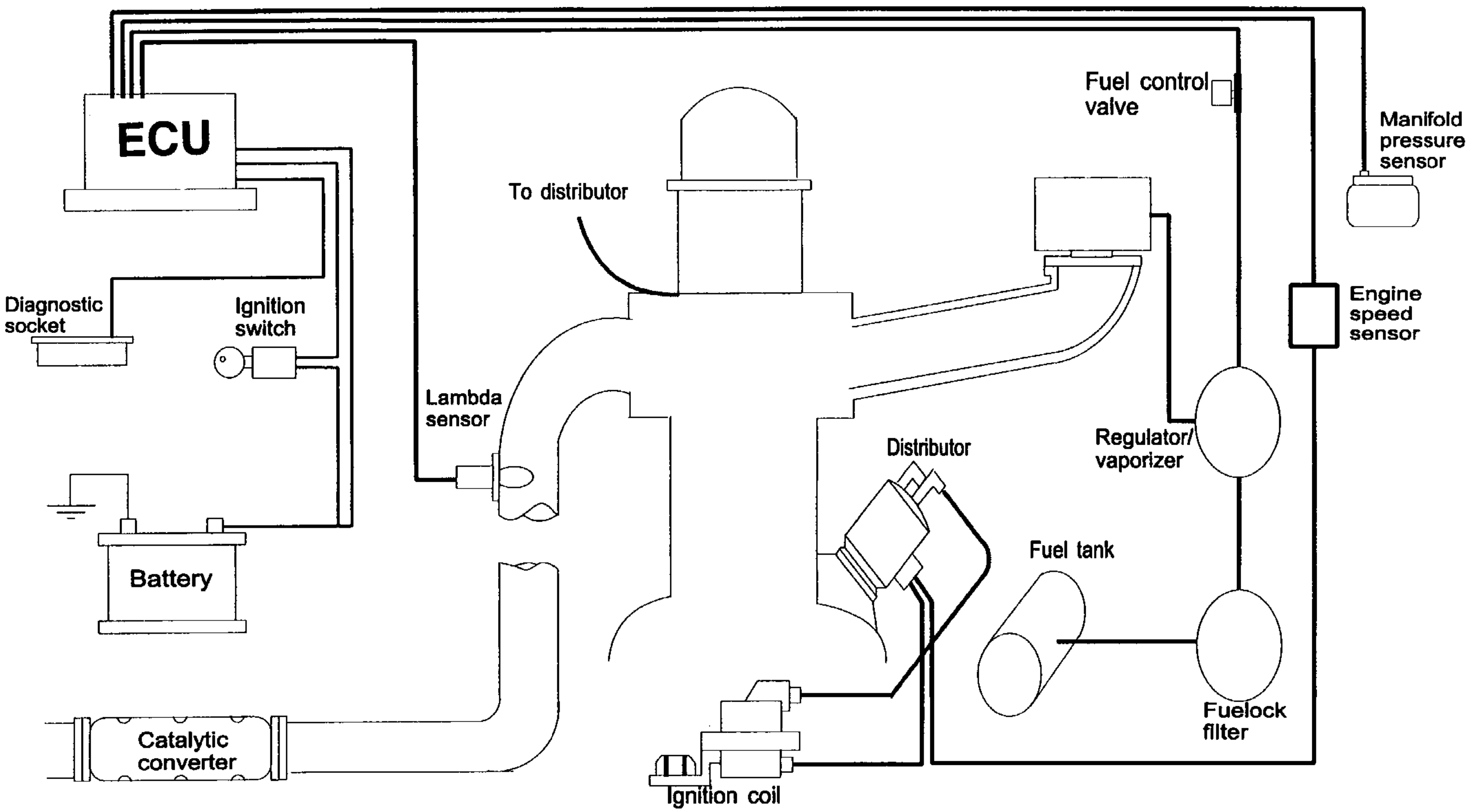

FIGURE 25. SCHEMATIC OF SECOND CLOSED-LOOP CONTROL SYSTEM

C. Task 2.3 - Develop and Test the Emission-Controlled Gasoline/LPG Engine Systems

1. Engine B Emission Control System Development

Development work on Engine B was begun using the third closed-loop control system described in Section III.B. This system provided the greatest control flexibility and was expected to achieve the largest emission reductions. An OEM converter was also selected for initial development efforts. System components included:

- Wiring harness
- Electronic engine control module (ECM)
- Exhaust gas oxygen (EGO) sensor
- Air and fuel mixer (carburetor)
- Fuel pressure regulator, and temperature control unit
- Fuel shut off regulator
- Intake manifold absolute pressure (MAP) sensor, analog signal to ECM
- Intake manifold pressure sensor, digital signal to fuel shut off regulator
- Catalytic converter

During development, SwRI monitored engine air/fuel ratio (AFR) with a Horiba wide-range AFR sensor, along with the signal from the control system's EGO sensor, and the duty cycle of the fuel-control valve (FCV) in order to assess the closed-loop operation of the system. The default calibration in the ECM allowed the AFR to dither about stoichiometric with excursions far into both lean and rich regimes. In addition, the AFR stayed lean or rich for a longer time than desired. Initial development of the control system focused on achieving tight control of AFR near stoichiometric. To accomplish this, six calibrations of FCV control parameters were evaluated until improved air/fuel ratio control was achieved.

Table 63 shows the initial developmental results obtained with the third closed-loop control (CLC) system, along with open-loop baseline results for comparison. The catalyst did not have any run-in hours on it, so these data reflect fresh catalyst performance. The results indicated that the baseline fuel calibration was lean of stoichiometric, which is standard practice for indoor lift truck operation. Data also showed that operation in closed-loop control without a catalyst did not significantly reduce emissions with this engine. Modal data indicated that if Lambda were kept at about 0.99, all reduction efficiencies should be optimized.

TABLE 63. ENGINE B DEVELOPMENTAL TEST RESULTS WITH THIRD CLOSED-LOOP CONTROL SYSTEM, ISO 8178-C2 CYCLE, LPG FUEL

Test Description	Emissions, g/hp-hr				BSFC, lb/hp-hr
	HC	NO_x	$HC+NO_x$	CO	
Average Baseline	0.94	11.7	12.6	7.37	0.526
Closed-Loop without Catalyst	1.26	10.5	11.8	19.2	0.572
Closed-Loop with Catalyst	0.35	0.4	0.49	2.96	0.558
Closed-Loop with Catalyst Reduction from Baseline, %	63%	99%	96%	60%	-6%

Following initial tests with the third CLC system, the second CLC system was installed and evaluated. It uses the same internal logic and closed-loop control parameters as the first system once it is in CL control mode. The difference between the systems is that in order to reach stoichiometric more quickly, the second controller references an initial duty cycle for the FCV from a three-by-three matrix of speed and intake manifold pressure whenever speed and/or load are disturbed due to transient engine operation. Once at stoichiometric during steady-state operation, FCV control is such that the first and second systems behave identically, and would be expected to produce similar emissions.

Table 64 shows emission test results from engine B equipped with the second CLC system, and includes results from the third system for comparison. Results show that the second system operates leaner than the SwRI-developed third system. Because of the leaner operation, HC and CO emissions were lower with the second system but NO_x emissions were higher, which caused a net increase in $HC+NO_x$ emissions. The second control system is not adjustable through software, and has a default calibration which must be adaptable to any engine and fuel system configuration to which it may be applied. The default calibration is therefore flexible to accommodate a variety of engine configurations. During the tests, we noted that AFR repeatability was not as good as observed with the third CLC system, and that it occasionally took the second system longer to reach stoichiometric. During Test No. DB-2 in Mode 4, the engine ran leaner on average than had previously been noted, therefore this mode was repeated. When the engine again operated leaner in Test No. DBC-2, we decided to test the system "as is" in each mode because we could not adjust its control parameters.

Following tests with the second CLC system, we continued development of engine B using the third CLC system. Figure 26 shows data taken during developmental tests with the sixth control calibration (B-6). The wider-ranging AFR and richer operation in Mode 2 can be compared to leaner and tighter control in Modes 4 and 6. Further emissions reductions were considered achievable if tighter AFR control could be maintained in the different test modes.

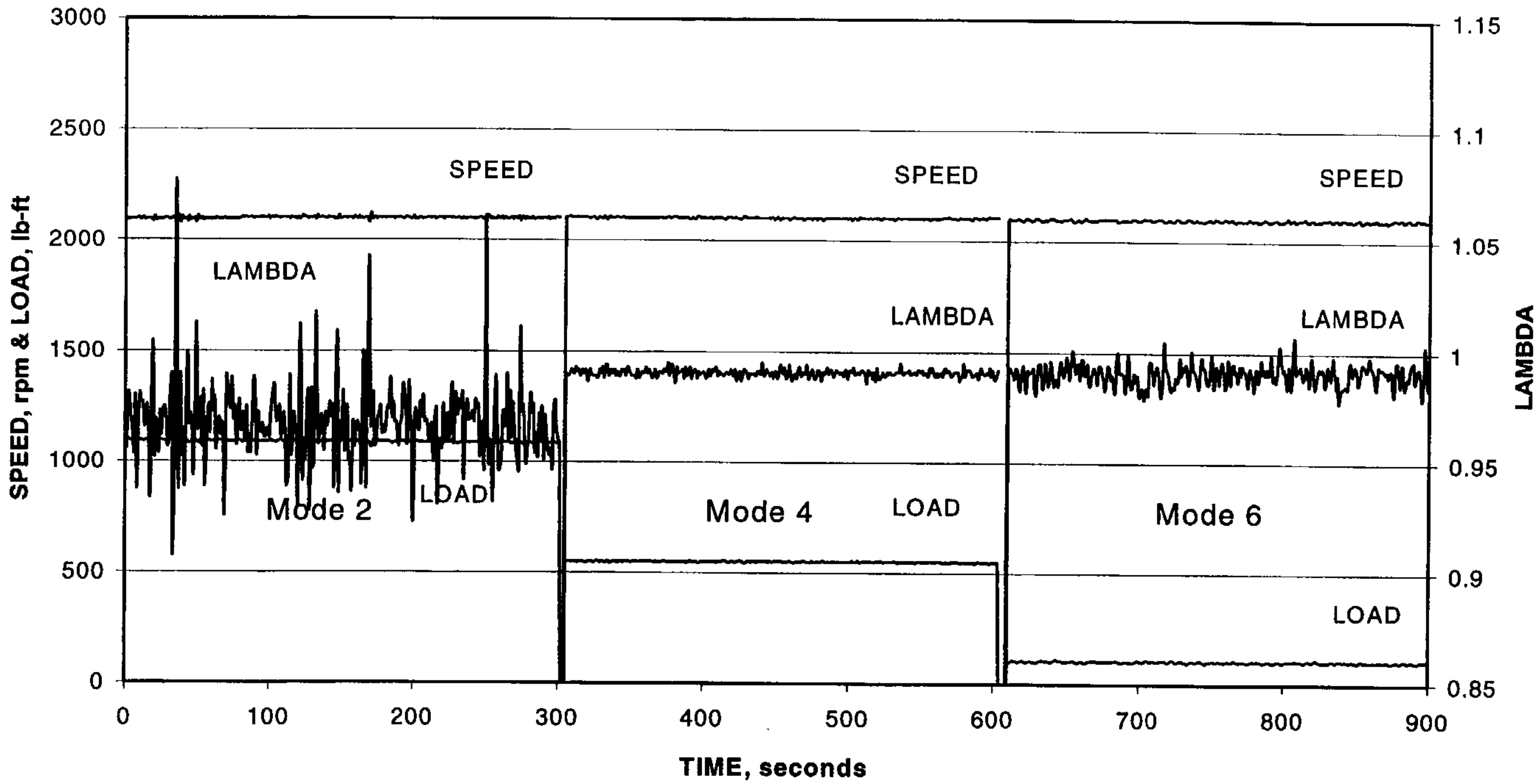

FIGURE 26. ENGINE B DEVELOPMENT WITH THIRD CLC SYSTEM, CALIBRATION B-6, MODES 2, 4, AND 6

TABLE 64. ENGINE B DEVELOPMENTAL TEST RESULTS ON LPG FUEL

Test Description				Emissions, g/hp-hr					
Test No.	CLC System	Catalyst	Notes	HC	CO	NO_x	$HC+NO_x$	CO_2	BSFC, lb/hp-hr
DB-1	Third	none	B-6 calibration	1.26	19.2	10.5	11.8	743	0.572
DBC-1	Third	OEM	B-6 calibration	0.35	2.96	0.14	0.49	751	0.558
DB-2	Second	none	M5 re-run when it went lean	1.17	17.4	9.79	11.0	730	0.561
DBC-2	Second	OEM	Lean in Modes 4, 5, 6	0.15	1.16	5.40	5.55	752	0.556
DB-3	Second	none	Lean in Modes 4, 5, 6, and took a long time to settle	1.16	14.1	9.74	10.9	713	0.544
DBC-3	Second	OEM	Control OK	0.10	1.06	0.88	0.98	768	0.567

The fuel control calibration in the third CLC system was incrementally modified several times in attempts to achieve lower emissions. Although we were successful in reducing HC emissions, CO and NO_x emissions increased. Emission results with the B-24 calibration (Test DBC-6) are shown in Table 65. To further reduce emissions, a larger volume catalytic converter from a Ford Ranger light-duty truck was procured and installed in place of the OEM converter. An emission test was performed after four hours de-greening of the catalyst.

TABLE 65. ENGINE B DEVELOPMENTAL TEST RESULTS WITH THIRD CLC SYSTEM

Test Description	Test Number	Emissions, g/hp-hr						BSFC, lb/hp-hr
		HC	CH_4	NMHC	NO_x	$HC+NO_x$ ($NMHC+NO_x$)	CO	
CL control, OEM catalyst, B-24 calibration	DBC-6	0.21			0.50	0.71	5.88	0.559
CL control, Ranger catalyst, B-6 calibration	DBC-7	0.09			0.01	0.10	2.10	0.542
CL control, Ranger catalyst, Durability baseline test with unregulated emissions, mixed calibration	DFB-1B	0.26	0.04	0.22	0.04	0.30 (0.26)	4.24	0.547
CL control, Ranger catalyst, Durability baseline test with unregulated emissions, mixed calibration	DFB-2B	0.25	0.06	0.19	0.02	0.27 (0.21)	4.06	0.557
CL control, Ranger catalyst, Durability baseline test, B-24 calibration	DFB-3	0.19			0.01	0.20	4.13	0.554

Results of emission tests performed with the Ranger catalyst are shown in Table 65. Test number DBC-7, performed with engine calibration B-6, produced very low emission rates of 0.10 g $HC+NO_x$/hp-hr, and 2.10 g CO/hp-hr. Tests DFB-1 and DFB-2 were performed with unregulated emissions also measured. It was noted, during these tests, that the engine ran much richer in mode 4 than during test DBC-7. We decided that the B-6 calibration was not robust enough to consistently control mode 4 to the same AFR. The B-24 calibration was re-input into the engine control module and showed much better repeatability. Duplicate mode 4 emission tests were performed with unregulated emissions measurement, and the weighted modal emission results were recalculated. These recalculated results are shown in Table 65 with revised test numbers DFB-1B and DFB-2B. An additional emission test (DFB-3) was performed (without unregulated emissions measurement) to confirm the validity of the B-24 calibration results with respect to results calculated using the combined data. Detailed modal data from the tests summarized in Table 65 are included in Appendix C.

The third CLC system control algorithm has separate inputs for enrichment and enleanment switch points based on EGO sensor output. For example, enrichment could be controlled to begin when the EGO feedback increased above 0.5V, and enleanment could be controlled to begin when EGO feedback decreased below 0.45V. By changing these switch points, the overall air/fuel ratio (AFR) can be biased lean or rich; and by increasing or decreasing the voltage difference between the two switchpoints, a larger or smaller deadband could be achieved in which fuel flow would not be adjusted. Control of deadband width was useful because the fuel system responded more quickly to enrichment commands than to enleanment commands. By increasing the deadband, the AFR could be kept lean for a longer time to compensate for quicker enrichment response.

Another independent control variable in the third CLC system is the enrichment and enleanment step size for the Fuel Control Valve's duty cycle. During development, the enrichment step was set smaller than the enleanment step to achieve tighter AFR control, and to compensate for quicker enrichment response. Step sizes can also be changed for different engine speeds, but cannot be changed for different engine loads. Because the majority of the emission test is performed at intermediate speed, it would have been useful to have the ability to also vary the step size based on engine load.

Following development of an Engine B calibration meeting program goals, unregulated emissions of formaldehyde, acetaldehyde, benzene, 1,3-butadiene, and styrene were measured. Results are summarized in Table 66. Detailed speciation results are included in Appendix C.

Through application of aftertreatment, unregulated emissions of formaldehyde and acetaldehyde were both reduced by over 99% from baseline levels of 85.7 mg/hp-hr and 15.5 mg/hp-hr, respectively. Benzene emissions were reduced by 40% from a baseline level of 0.4 mg/hp-hr, and 1,3-butadiene emissions were reduced by 86% from a baseline level of 1.4 mg/hp-hr.

A peak was found in the speciation gas chromatogram at the elution time for styrene in only one mode of the two baseline tests performed (CHEM 2B). However, with LPG fuel it is not a reasonable exhaust constituent to expect to find. Therefore, we assigned it as an unidentified C9-C12+ compound. Styrene was not found in any test mode once aftertreatment was applied to the engine.

TABLE 66. ENGINE B BASELINE AND DEVELOPMENTAL EMISSION RESULTS
ISO 8178-C2 CYCLE, LPG FUEL

Result	Test				
	Baseline Mean	Devel. DFB-1B	Devel. DFB-2B	Developmental Mean	Reduction, %
Emissions, g/hp-hr					
HC	0.94	0.26	0.25	0.26	72
CH_4	0.03	0.04	0.06	0.05	NA
NMHC	0.91	0.22	0.19	0.21	77
NOx	12.17	0.04	0.02	0.03	>99
CO	4.52	4.24	4.06	4.15	8
NMHC+NOx	13.08	0.26	0.21	0.24	98
BSFC, lb/hp-hr	0.548	0.547	0.557	0.552	-1
Emissions, mg/hp-hr					
Formaldehyde	85.7	0.14	0.22	0.18	>99
Acetaldehyde	15.5	0.04	0.00	0.02	>99
Benzene	0.4	0.24	0.23	0.24	40
1,3-butadiene	1.4	0.29	0.10	0.20	86
Styrene	0.00	0.00	0.00	0.00	NA

2. Engine E Emission Control System Development

An alternative closed-loop (CL) control system was located for use with engine E to replace Zenith's ZEEMS closed-loop control system, which was not ready in time for development work. We selected the Electromotive Total Engine Control (TEC) system based on prior experience. The TEC system utilizes PC-based control, which can be reconfigured while the engine is running, which helps shorten development time. In open-loop control, the TEC system uses a speed-density algorithm for air/fuel control. Spark timing is electronically controlled with Electromotive's Direct Ignition System (DIS), which uses a 60-minus-2 tooth gear and simultaneously fires two plugs directly from twin tower coils. A TEC-II system, which combines the coils, injection control, and computer in one package was procured for application to Engine E. System components included

- Wiring harness
- Electronic engine control module (ECM)
- Exhaust gas oxygen (EGO) sensor
- Throttle body (includes injector, and fuel pressure regulator)
- Magnetic pickup (speed sensor)
- 60-minus-2 tooth gear (on crankshaft)
- Electronic ignition coils
- Intake air temperature sensor
- Engine temperature sensor

Engine E was installed and setup in Cell 2 with the TEC-II system. Air injection system components including an air pump, hoses, and switching valves were procured and installed. Brackets were fabricated for mounting of components. Two heavy-duty SI truck engine dual-bed converters were also purchased for use with this engine. A 2.5L GM engine throttle body and intake air filter housing were adapted and installed on the engine.

Although the preferred emissions reduction strategy would have been stoichiometric operation with a three-way catalyst for exhaust aftertreatment, engine protection issues constrained this option. Since the engine was air-cooled, the original design relied on a very rich fuel setting to keep temperatures low. Running the engine leaner at high loads would cause it to overheat. Engine temperature was monitored through spark-plug seat measurements, on which the manufacturer imposed a limit of 500°F.

With the foregoing as a primary restriction, the following emission reduction strategy was adopted. Air/fuel ratio was adjusted up to the limits of engine temperature constraints. At lighter loads where lower temperatures allowed, stoichiometric closed-loop fuel control was used. In more highly loaded modes, a rich open-loop calibration was employed. The converter was installed with air injection available both before the front catalyst bed and between the two beds. During open-loop operation when the engine was running rich, air could be injected at both locations. No air injection was to be used during closed-loop operation.

During development of the calibration, it was confirmed that the engine could successfully be run in closed-loop, stoichiometric operation for all operating points except at wide open throttle. It was only at, or near, WOT that the fuel mixture had to be kept rich, at an AFR of 11, in order to prevent overheating. Closed-loop control with a rich bias (AFR of 14) was employed at all other engine loads.

Air injection flow rate at WOT was adjusted for best emissions reduction without overheating the catalyst. Using the real-time emissions measurement system, air injection rates to both front- and mid-bed positions were adjusted until target emission reductions were achieved within acceptable converter temperatures.

Efforts to reduce CO emissions at WOT were limited by two factors. The primary consideration was the spark plug seat temperature ceiling of 500°F. This was compounded by the fact that the engine has poor fuel distribution among the four cylinders. During initial mapping exercises on the stock engine, it was discovered that cylinder number two ran much hotter than the other cylinders. As shown in Table 67, the conversion to throttle-body fuel injection did not remedy this problem. Since designing a new intake manifold was beyond the scope of this project, emission reduction efforts for full load operation were limited. The high temperature of cylinder two prevented a leaner fuel setting, which would have further reduced engine-out CO levels. In turn, high engine-out CO levels resulted in high catalyst temperatures. To protect the catalyst, it was decided to keep its outlet temperature below 1650°F. Table 68 shows the range of catalyst temperatures observed at different air injection rates.

Since the engine was scheduled for service accumulation as a pump drive, the final emissions test was performed according to the D2 5-mode test cycle for constant-speed engine applications. Results are summarized in Table 69, along with those of the baseline tests. Detailed emission test results are included in Appendix D. Developmental efforts reduced HC and CO by 97 percent and 94 percent, respectively. NO_x emissions in the baseline configuration were low due to the rich fuel setting. However, even with the leaner operation of the final calibration, use of the three-way catalyst achieved a 14 percent reduction in NO_x emissions. The leaner fuel calibration also resulted in a 16% improvement (reduction) in fuel consumption. Following development, Engine E met the proposed HC+NO_x standard of 3 g/hp-hr, and the proposed CO standard of 37 g/hp-hr.

TABLE 67. ENGINE E SPARK PLUG SEAT TEMPERATURES

Configuration	Spark Plug Seat Temperatures, °F			
	CYL 1	CYL 2	CYL 3	CYL 4
Stock	466	519	492	474
Emissions-Optimized	435	513	457	494

TABLE 68. EFFECT OF ENGINE E AIR INJECTION RATE ON CATALYST TEMPERATURE AND CO EMISSIONS

Air Injection Control Valve Position			CO Emission, g/hp-hr	Catalyst Outlet Temp, °F
Front	Back	Bypass		
3 Turns Open	2 Turns Open	Full Open	195	1544
Full Open	Full Open	Full Open	180	1616
Full Open	Full Open	1.5 Turns Closed	143	1651
Full Open	Full Open	2 Turns Closed	28	> 1700
NOTE: Full range of each valve is 4.5 turns.				

TABLE 69. ENGINE E BASELINE AND DEVELOPMENTAL EMISSION RESULTS ISO 8178-D2 CYCLE, GASOLINE FUEL

Result	Test		
	Baseline Mean	Developmental 5-MODE-4	Reduction, %
Emissions, g/hp-hr			
HC	9.86	0.25	97
CH_4	1.55	0.09	94
NMHC	8.21	0.15	98
NOx	1.65	1.42	14
CO	449	28.4	94
NMHC+NOx	9.86	1.57	84
BSFC, lb/hp-hr	1.051	0.881	16
Emissions, mg/hp-hr			
Formaldehyde	91.4	0.00	100
Acetaldehyde	9.33	2.02	78
Benzene	374	23.8	94
1,3-butadiene	67.1	0.06	>99
Styrene	45.1	0.00	100

Unregulated emissions were measured on Engine E after developmental efforts were completed, and these data are included in Table 69. Formaldehyde emissions were reduced below detection limits by the application of aftertreatment and closed-loop control. Acetaldehyde emissions were reduced by 78 percent from the baseline level of 9.33 mg/hp-hr. Benzene emissions, which were a significant portion (4%) of total speciated HC emissions from the baseline engine, were reduced by 94 percent from 374 mg/hp-hr. 1,3-butadiene emissions were reduced by over 99 percent from the baseline level of 67.1 mg/hp-hr. Baseline mean brake-specific styrene emissions were 45.1 mg/hp-hr, and no styrene was detected from the developmental engine. Detailed modal emissions and speciation data are included in Appendix D.

D. Task 2.4 - Test Durability of the Emission-Controlled Gasoline/LPG Engine Systems

1. Engine B Emission Control System Durability

Engine B was installed in an SwRI forklift for service accumulation. The forklift was originally powered by a 2L gasoline engine. The LPG engine, although of slightly larger displacement, is based on the same engine block, and was a bolt-in replacement for the gasoline engine. An LPG fuel tank was mounted on top of the counterweight, and the catalytic converter was installed in the vehicle exhaust system in the space inside the counterweight. The forklift was in daily use for moving fuel drums and other materials used by the Automotive Fuels and Fluids Research Department.

A data acquisition system was installed on the forklift to monitor engine operation during service accumulation. Data was recorded at 1 Hz for the first 5 minutes after every engine start, and thereafter data was stored as 1 minute averages. The following data was acquired:

- Intake air temperature
- Exhaust temperature before the catalyst
- Exhaust temperature after the catalyst
- Intake manifold depression
- Engine speed
- Throttle position

The purpose of the data acquisition was to provide a record of operation in the event of problems. It was not intended to provide a characterization of vehicle operation for detailed analysis.

The forklift operator reported no problems with the modified forklift, and was satisfied with the engine's performance. Hour accumulation, however, was building slowly. To accelerate the service accumulation, we searched for a local user with a higher usage rate. We found an operation at the HEB Grocery chain's main warehouse where trailers which have been unloaded are sent for final cleaning. Empty boxes and pallets are removed from the trucks, and compacted trash is hauled away from the unloading area. The warehouse operates its equipment around the clock, seven days per week.

The 250 hours of durability accumulation was completed in an additional two weeks. Eighty-three hours of usage were at SwRI moving drums and pallets of fuels, and 167 hours of usage were at the grocery warehouse performing clean-up activities. No operational problems were reported at either location. We would characterize the forklift service accumulation as light commercial, because no great deal of heavy lifting was required.

Following service accumulation, the engine was removed from the forklift and reinstalled in an emissions test cell. The engine started and ran well for about 20 minutes, but then stumbled and died. The cause was found to be a wiring problem at test stand. Following repair, the engine was found to be operating lean of stoichiometric in the under 50 percent load modes. Since the engine was operating acceptably, it was decided to perform an "as is" emissions test before beginning to troubleshoot the problem. Results are presented in Table 70 (DFB-4). Lean engine operation in the lower load modes resulted in high NO_x emissions.

TABLE 70. ENGINE B DURABILITY TEST RESULTS WITH THIRD CLC SYSTEM ISO 8178-C2 CYCLE, LPG FUEL, B-24 CALIBRATION

Test Description	Test Number	Emissions, g/hp-hr						BSFC, lb/hp-hr
		HC	CH_4	NMHC	NO_x	$HC+NO_x$ ($NMHC+NO_x$)	CO	
"As-received" - lean CL control, Ranger catalyst 250-hr durability test	DFB-4	0.19			8.97	9.16	0.65	0.557
After repair - stoichiometric CL control, Ranger catalyst 250-hr durability test	DFB-5	0.08	0.03	0.05	0.53	0.61 (0.58)	3.51	0.558
After repair - stoichiometric CL control, Ranger catalyst 250-hr durability test	DFB-6	0.07	0.03	0.04	0.15	0.22 (0.19)	2.79	0.558
Average of DFB-5 and DFB-6	Average	0.08	0.03	0.05	0.34	0.42 (0.39)	3.15	0.558
Durability baseline test - 0 hr CL control, Ranger catalyst	DFB-3	0.19			0.01	0.20	4.13	0.554
Deterioration Factor (DF) (additive)		-0.11	-0.02	0.16	0.33	0.22 (0.15)	-0.98	

Following this test, the fuel system was carefully examined and two problems were found. The gas regulator had a small fuel leak, which was repaired by rebuilding the regulator. This had no effect on engine operation. The second problem was a yellowish, viscous liquid, coating the inside of the fuel valve. This was the cause of the control problem, and after the valve was cleaned, the system returned to normal stoichiometric control. This contamination incident was discussed with the control system manufacturer, and they indicated that it was likely an additive that is sometimes added to commercial LPG. Two tests were run (DFB-5 and 6) following cleaning, and these are also presented in Table 70. Detailed modal results are included in Appendix E.

Results show that good, low emission results could be obtained with a properly operating control system. Results are not equivalent to the 0-hour result, but this likely is more due to drift of the hardware and its calibration than to catalyst deactivation. This is reflected by the variation observed between Tests DFB-5 and DFB-6.

Additive deterioration factors (DFs) were calculated from these results, and these are also presented in Table 70. DFs for CH_4, NMHC, and NMHC+NO_x are based on the 0-hour Developmental Mean results reported in Table 66, since methane data were not taken in the durability baseline test DFB-3. Deterioration factors reflect the changes in emissions between zero hour and aged performance, typically due to catalyst deactivation and changes in other system components. Negative DFs were calculated for HC, CH_4, and CO. Since catalyst-based emission control systems do not usually improve over time, these values are not realistic and should not be used to predict in-use results. Rather, they reflect the short durability interval studied (250 hrs), and effects of engine control system drift.

Thus, the durability demonstration with Engine B showed:

1. The system performed acceptably throughout the 250-hour durability period, and no complaints regarding operational problems were received.

2. A small leak in the gas regulator was discovered after durability service and repaired.

3. System emissions performance was compromised by a fuel contamination incident.

4. When restored to proper operation, the system performed correctly and gave good, low emission results.

5. Changes in emission results between 0 and 250 hours likely reflect system drift more than deterioration or deactivation.

6. Emission control systems need to be robust and repeatable to deliver consistent performance over time.

2. Engine E Emission Control System Durability

SwRI selected an appropriately sized water pump for use with Engine E. A skid mount was built for the engine and pump system, which was placed in service on the Institute grounds. While plans originally were to put the pump in service on a farm for irrigation, another approach was needed because field watering was low at the time (fall) of the durability accumulation. The system was set up to pump water out of and back into the Emissions Research Department cooling tower. While this was not real irrigation service, it followed the same operational pattern, and should have provided the same durability environment.

The pump was operated continuously with periodic shut-downs for maintenance. Every morning, the engine was shut-down, and the oil level was checked. During the day, the engine was operated at 1800 rpm, which ran the engine at approximately 75 percent of full load. In the evening, the engine speed was dropped to 1700 rpm, which reduced the load to approximately 50 percent. Every 50 hours, the oil and filter were replaced, as specified in the owner's manual.

At approximately 240 hours of durability accumulation, Engine E began switching from rich to lean at a slower rate than programmed, causing engine speed to surge. The engine control software reported an EGO failure, so a new EGO sensor was installed on the engine, but the failure continued to be reported. The control software EGO failure criterion is lean operation for an extended period. Since the new sensor was operating like the old sensor, we looked for other problems that could produce lean operation.

Other engine sensors were checked including the manifold air pressure (MAP) sensor, intake air temperature sensor, coolant temperature sensor (oil temperature on this engine), and throttle position sensor (TPS). Fuel pump pressure and engine governor operation were also checked, and the software was reloaded into the ECU.

The cause of the problem was found after reviewing ECU control settings. In the EGO feedback control programming, a switch is included which disables closed-loop (CL) control until the coolant temperature is above 30°C (86°F). Since this is an air-cooled engine, the coolant reading is taken at the oil gallery on the side of the engine. The problem manifested itself initially during a cold morning where the engine had cooled sufficiently to disable CL control. Thereafter, the weather stayed cool, and the engine oil did not get hot enough to enable CL control. The program was revised to enable CL control at 5°C, and the engine then ran correctly, so service accumulation was completed.

The engine was reinstalled in an emissions test cell, and two 5-mode D2 cycle tests were performed. Results are presented in Table 71. Detailed modal results are included in Appendix E.

TABLE 71. ENGINE E DURABILITY TEST RESULTS ISO 8178-D2 CYCLE, GASOLINE FUEL

Test Description	Test Number	Emissions, g/hp-hr						BSFC, lb/hp-hr
		HC	CH_4	NMHC	NO_x	$HC+NO_x$ ($NMHC+NO_x$)	CO	
250-hr durability test CL control, TWC w/air @ WOT	5-Mode-5	0.17	0.13	0.03	0.14	0.31 (0.17)	39.7	0.922
250-hr durability test CL control, TWC w/air @ WOT	5-Mode-6	0.17	0.14	0.03	0.08	0.25 (0.11)	44.8	0.920
Average of 5-Mode 5&6	Average	0.17	0.13	0.03	0.11	0.28 (0.14)	42.2	0.921
Durability baseline test - 0 hr CL control, TWC w/air @ WOT	5-Mode-4	0.25	0.09	0.15	1.42	1.67 (1.57)	28.4	0.881
Deterioration Factor (DF) (additive)		-0.08	0.04	-0.12	-1.31	-1.39 (-1.43)	13.8	

The engine and emission control system performed well following durability accumulation. HC+NO_x emissions were actually lower at 250 hours than at zero hours. It appears that the engine was running slightly richer following durability, which accounts for the lower NO_x emissions. This, in turn, increased CO emissions, which slightly exceeded the 37 g/hp-hr standard after durability.

Additive deterioration factors (DFs) derived from these data are also presented in Table 71. Negative DFs were calculated for HC, NMHC, NO_x, HC+NO_x, and NMHC+NO_x. Since it is unlikely for catalyst-based emission reduction systems to have negative DFs, these factors are unrealistic and should not be used to predict in-use emissions. As explained above, the DFs were influenced by the engine's A/F drift between the 0- and 250-hour test points.

Control system settings and engine sensor operation were reviewed, looking for a reason for the engine's richer operation. No problems were found, and so we concluded that this emission control system could benefit from further development to create a more stable calibration. The TEC II control system has many features which could be further tuned to tailor its operation for this engine system.

The durability demonstration with Engine E showed:

1. The system performed well throughout the durability period, although a control setting required adjustment near the end of the durability to maintain proper operation in the cooler outdoor weather.

2. Good, low emission results were obtained after durability. HC+NO_x emissions decreased and CO emissions increased, compared to zero-hour results.

3. Control system drift observed between 0 and 250 hours could likely be reduced through further development work.

IV. SUMMARY AND CONCLUSIONS

A Technical Advisory Committee (TAC) was formed with representatives from equipment, engine, fuel system, and catalyst manufacturers, and industry associations. Two TAC meetings were held, and input was received on a number of topics including: category equipment population and sales, emission reduction technology development and manufacturing issues, typical equipment operating modes, recommendations regarding test cycles and procedures, and emission reduction technology costs. TAC members also provided engines and other hardware for use in this project.

All project objectives have been accomplished. First, it was determined that it is feasible to transfer TWC and other advanced emission reduction technologies to off-road gasoline and LPG engines. Second, emission test procedures appropriate for category equipment were defined. The seven-mode ISO 8178-C2 cycle is recommended for variable speed equipment such as forklifts, baggage handling and tow/push equipment, scrubbers/sweepers, turf care equipment, and specialty vehicles. The five-mode ISO 8178-D2 cycle is recommended for constant speed applications such as generator sets, aircraft ground power, and refrigeration units. A research cold-start test cycle was also defined for use in obtaining baseline emissions data.

Required reductions from baseline emission levels necessary to meet SIP goals were derived. Based on the EEA category equipment inventory and other assumptions, a 98 percent reduction in ROG, and a 73 percent reduction in NO_x is required to meet 2010 SIP goals. Assuming the category equipment baseline emission value is represented by the mean of the data summarized in Table 15, emission standards required to meet SIP goals were derived as shown in Table 72.

TABLE 72. EMISSION STANDARDS REQUIRED TO MEET SIP GOALS

	Emissions, g/hp-hr	
	HC	NO_x
Mean Baseline from Table 15	3.96	9.56
Required Reduction for SIP	97.7%	73.3%
Resulting Standard	0.09	2.55

Cost effectiveness analysis was performed based on these calculated emission reductions. Category equipment population and usage characteristics were analyzed. Non-preempted equipment (M11) and preempted equipment (M12) were analyzed separately. Cost estimates were developed for recommended emission control technologies. Retail price equivalent (RPE) costs for application of these technologies were determined using the EPA RPE equation. Daily emission inventories were calculated for both controlled and uncontrolled engines for both M11 and M12 equipment. Cost effectiveness analysis was performed based on the incremental RPE and the emission reduction realized by the emission control technology. Results were presented for both non-preempted equipment, and all equipment, separated by industrial, agricultural, and construction categories. Cost effectiveness based on HC+NO_x emission reductions ranged from $0.08 per pound for preempted LPG construction equipment, to $0.40 per pound for preempted gasoline agricultural equipment.

The third project objective was to demonstrate that TWC technology could meet the proposed standards by applying the technology to off-road engines and performing emissions durability testing. Systems were designed and installed on engines B and E. Both systems included closed-loop, stoichiometric fuel control, and three-way catalysts. Baseline controlled emission data was taken, and then the two engines were placed in service for 250 hours.

Engine B was installed in a forklift and placed in service at SwRI handling drums of fuel. It was later transferred to a local grocery chain warehouse to increase its rate of service accumulation. Engine E was coupled to a water pump and placed in service as a pump drive. Both engines successfully completed their service intervals, although Engine B suffered a fuel contamination incident which required cleaning of the fuel control valve, and Engine E required a setting change in its software to enable it to run properly in cooler weather.

During the course of this project, the California Air Resources Board adopted emission standards and test procedures for this category. The regulations cover new 2001 and later off-road large spark-ignition engines 25 horsepower or above. The regulations exclude construction and farm equipment engines below 175 horsepower, which are preempted from state control by the 1990 federal Clean Air Act Amendments. However, in January 1999, EPA proposed a finding that these engines contribute to air quality non-attainment, and indicated that they will likely propose emission regulations for these engines similar to those of California.

California has defined two tiers of emission standards for engines greater than one liter displacement. Most engines in this category, and <u>all</u> the engines in this project have displacements greater than one liter. The two tiers of standards are equivalent numerically, as summarized below.

TABLE 73. CARB LSI ENGINE EMISSION STANDARDS, >1L DISPLACEMENT

Tier	Application	Standards, g/hp-hr		Useful Life
		NMHC+NO_x	CO	
1	2001-2003	3.0	37	N/A
2	2004 +	3.0	37	5000 hrs. or 7 yrs.

The Tier 1 standards will be implemented through a phase-in beginning in 2001. For this tier, manufacturers are responsible for meeting the standards only when the engine is new. Tier 2 standards, on the other hand, must be met throughout the engine's useful life, which is currently defined as 5000 hours or seven years. (Engines of one liter displacement or less have a different standard patterned after the small off-road engine regulations.) Both Engines B and E met CARB's large spark-ignited (LSI) standards, as summarized in Table 74, except for Engine E's CO emissions following durability, which slightly exceeded the standard.

TABLE 74. DEVELOPMENTAL ENGINE EMISSION RESULTS

Test Description	Emissions, g/hp-hr				BSFC, lb/hp-hr
	HC	NO_x	$HC+NO_x$	CO	
Engine B, C2 Cycle, LPG Fuel					
Original baseline, pre-control	0.94	11.7	12.6	7.37	0.526
Developmental baseline, CL control, TWC - 0 hr. Reduction from original baseline	0.19 80%	0.01 100%	0.20 98%	4.13 44%	0.554 -5%
Durability result, CL control, TWC - 250 hrs. Reduction from original baseline	0.08 91%	0.34 97%	0.42 97%	3.15 57%	0.558 -6%
Engine E, D2 Cycle, Gasoline Fuel					
Original baseline, pre-control	9.86	1.65	11.5	449	1.051
Developmental baseline, CL control, TWC - 0 hr. Reduction from original baseline	0.25 97%	1.42 14%	1.67 85%	28.4 94%	0.881 16%
Durability result, CL control, TWC - 250 hrs. Reduction from original baseline	0.17 98%	0.11 93%	0.28 98%	42.2 91%	0.921 12%
CARB LSI Standards ($NMHC+NO_x$)			3.0	37	

V. RECOMMENDATIONS

A major issue in the development of the LSI rule is extended catalyst durability. While this project included a limited durability demonstration, it is desirable to address this issue in greater depth. Key questions include: 1) can commercial catalysts perform acceptably over a period of 5000 hours, 2) what are typical deterioration factors for catalyst performance, and 3) are equipment fuel system calibrations sufficiently stable in long term operation? These questions need to be answered to provide confidence in the technologies industry will be relying on to meet this new rule.

There are several different ways to address extended durability. The most realistic would be to place a developed system in actual service, and monitor its performance and emissions at intervals out to 5000 hours. This process was begun with Engine B in the current project, and this could easily be extended. In-use hours can be accumulated in actual service at very low cost, and so this option has the advantage of being less expensive than laboratory aging. Alternatively, a developed system could be aged in the laboratory out to 5000 hours, with emission tests run at intervals. This has the advantage of more carefully controlled and monitored durability accumulation, but would be more expensive.

Another option would be to locate catalysts that have been in service on category equipment in the field for extended periods. These could be tested in the laboratory to determine their aged performance. This would provide some indication of catalyst durability, but could not provide an actual deterioration factor (DF) due to the lack of zero hour results. It would be best, of course, if the in-service engine and catalyst could be tested together. This would be considerably more difficult to arrange, but may be possible with the cooperation of an equipment user.

It may be desirable to evaluate the durability of a number of engines in different equipment applications. It may also be desirable to evaluate different catalysts and different fuel systems. All these options should be further discussed with industry to define a program that effectively addresses these key issues.

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